Horizon 2020

flora **robotica**

Societies of Symbiotic Robot-Plant Bio-Hybrids as Social Architectural Artifacts

Deliverable D3.2

Architectural propositions

Date of preparation: 2018/03/31	**Revision: 1 (r837)**
Start date of project: 2015/04/01	**Duration: 48 months**
Project coordinator: UzL	**Classification: public**
Partners: *lead:* **CITA**	*contribution:* **UzL, AMU, CYB, ITU, UniGraz**
Project website:	http://florarobotica.eu/

H2020-FETPROACT-2014

DELIVERABLE SUMMARY SHEET

Grant agreement number:	640959
Project acronym:	*flora robotica*
Title:	Societies of Symbiotic Robot-Plant Bio-Hybrids as Social Architectural Artifacts

Deliverable N^o:	Deliverable D3.2
Due date:	M36
Delivery date:	2018/03/31

Name:	**Architectural propositions**
Description:	Informing and steering growth of the plant symbiont requires goal state specifications (the desired shape and performance of the plant/robot hybrid) that relate to appropriate construction logics. Architectural goal states and methods of construction will be examined at a range of spatial, temporal and collective scales, that is, individual & collections of flora robotica. Two approaches will be developed: 1) Growing spaces - engaging with the full ‘growth career through continual reinterpretation of the system as it develops and matures. Propositions will be considered at multiple scales (states) and the transitions through scales (processes). Scales ranging from decoration, furniture, building component, building enclosure to landscape conditions will be considered. 2) Growing building components – steering growth towards defined target points with particular material, structural and aesthetic properties. The performance of building components will be discussed in comparison to those made from conventional materials. This work has a reciprocal relation to the work in WP1.

Partners owning:	**CITA**
Partners contributed:	**UzL, AMU, CYB, ITU, UniGraz**
Made available to:	public

Contents

1 Introduction

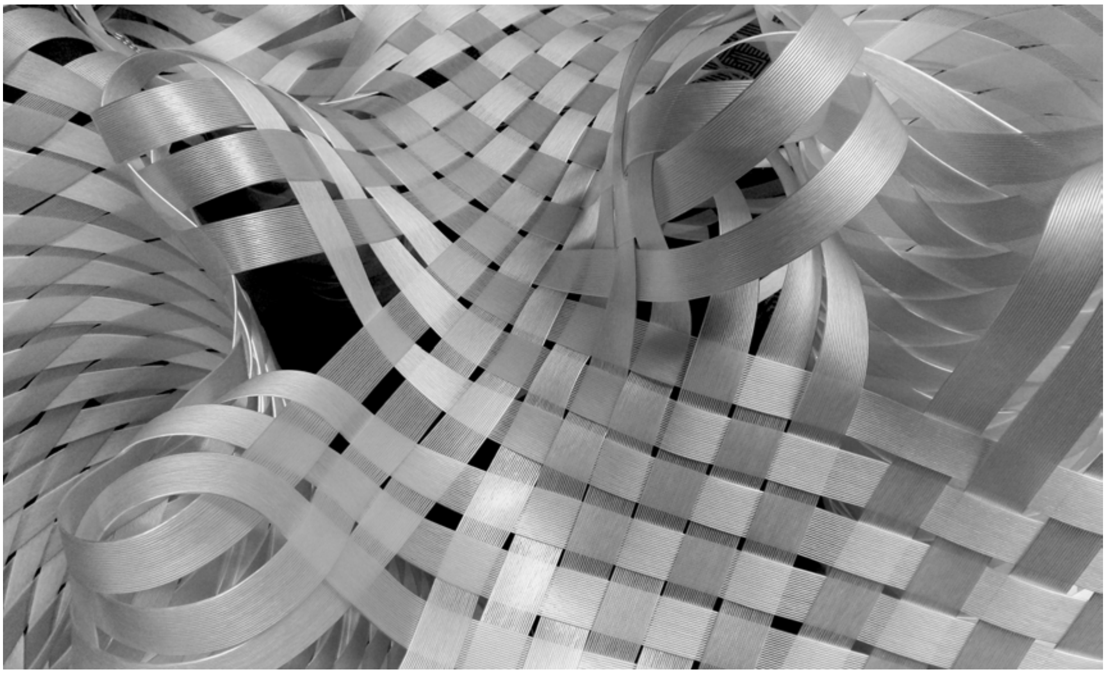
In WP3, the deliverables each align with one of the three tasks, which encompass complementary investigations into how *flora robotica* acts as a system of continuous architectural production. WP3 develops appropriate methods of architectural representation (T3.1, M1-M24), construction logics (T3.2, M12-M36) and the social and cultural dimension of *flora robotica* through the construction of a social garden (T3.3, M12-M48). The work package focuses on the Being aspect of the project, particularly in the context of Architecture. This deliverable reports the work completed as part of T3.2, which within WP3 overlaps with the timeline for T3.1. Therefore, some of the work reported here was developed simultaneously to work reported in previous deliverable D3.1, while some of it was developed afterwards and therefore builds more clearly from the conclusions and directions that were defined at the M24 review.

In the work for this task—focused on the construction logics developed for *flora robotica*—we conduct work that develops, implements, and makes propositions based on the comprehensive mechanical properties present in the construction logic of **Braid** and its architectural implications. There are a number of relationships between this work surrounding physical braids and braid mechanics, and other developments in the overall project. Firstly, in D3.1 we reported our modeling and representation approach for braid, which provides open-ended design tools and workflows for physical braids investigations. Secondly, in D1.3, autonomous fabrication and actuation hardware for braid is reported, which both feeds from and contributes to the simultaneous development of braid mechanics. Thirdly, hardware systems and plant growth dynamics are developed throughout WP1&2, which are all integrated on braided scaffolds in the holistic *flora robotica* system, thereby contributing constraints and ramifications to the mechanical development of the braids. The mechanical understandings of braid and of *flora robotica* overall, as well as the architectural propositions made from those understandings, will have significant impacts on the interactive artifacts and projections developed as part of the Social Garden in the future D3.3.

In the first chapter following this introduction, we report our development of braid as a construction method. Here we present some of the advantages—mechanical and otherwise—for which braid was selected as the overall construction logic, and introduce its key terminologies and mechanical concepts. Because mechanical stiffness is a crucial property in the context of construction on an architectural scale, we comprehensively develop strategies for steering braid's stiffness via material, filament organization, braid surface topology, and fastening of intersections. We then discuss new developments in our braid representation—in relation to the modeling of mechanical properties—and discuss the reciprocal relationship between braid mechanics in D3.2 and braid fabrication and actuation in D1.3.

The next chapter interprets, projects, and speculates about grown architectural spaces informed by braid's mechanical properties, especially through the consideration of the Growth Career. Architectural goal states, growth processes, and evaluation of targeted properties are presented through *Architectural Envisioning*, which underwent chronological development and resulted in a series of compelling, speculative, and evaluative propositions across scales and states. The non-mechanical elements of *flora robotica*—including a plant science perspective on the bio-hybrid ecosystem—are then reviewed, especially in terms of their interrelations and planned cohesion. Those elements are then considered in the simulated projection of an example growth, conducted through the Integrated Growth Projection (IGP) setup of D2.3. In the resulting example growth, we present for the first time an extensive architectural proposition that comprehensively considers all the hardware components and practical constraints of the integrated *flora robotica* system, and could realistically be produced by our hardware and mechanics at their current state of development in the project.

In the final chapter prior to the conclusion, we develop and discuss grown building components. We define functions and types for these components within the categories of structural elements and façade elements, exhaustively reviewing related grown and living components in both the scientific and grey literatures. We highlight the functions relevant to *flora robotica* and discuss how they could be implemented, and also propose several new strategies for producing structural elements in braided bio-hybrid systems. We review and discuss the potential impacts of electronic elements and plants on the mechanical performance of our braided scaffolds. We then discuss structural modeling of both braid and living plant structures, as well as the information available in the literature concerning structural comparisons between living plants and conventional construction materials. Finally, we discuss other performative properties of bio-hybrid structures, especially those which offer advantages over conventional construction materials, and discuss our planned demonstrator of one of those key advantages: *Self-repair*.

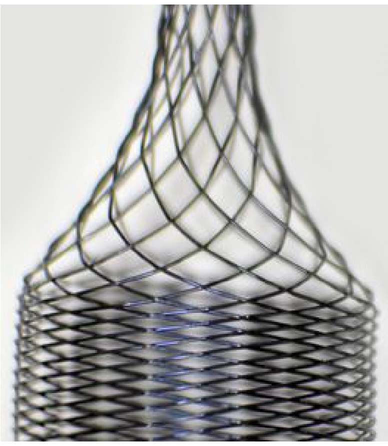


2 Developing Methods of Construction: Braid

As described in previous deliverables, the specification of mechanical scaffold in *flora robotica* has developed from scissor-scaffolds and strut-and-node to braided structures. Braid has a number of advantageous mechanical properties, which are detailed throughout this section. Besides its mechanical advantages, braid is also very receptive to a wide range of fabrication approaches, is robust enough for industrial applications, and is very friendly and approachable for new and uninitiated users. Additionally, braid as an approach is gaining momentum of adoption in new research applications. Since the time when flora robotica began using braid, some new relevant research projects were also published around the topic of braid. Below we briefly introduce the topic of braid, before continuing with the reporting of our mechanical investigations, material testing, modeling, and other work developing braid into a viable method of construction for plant-robot scaffolds.

Terminology There are a number of different definitions for the term *braid*, depending on the context, and it is often liberally exchanged with the term *weave*. Likewise, there are multiple terms that are used for the individual elements that comprise a braid, such as strand, cord, string, strap, etc. Most of these terms connotate a certain material—for example a 'string' would often be used to refer to an element made from natural fiber, or other fibrous material. Most of them also connotate a certain material cross-section, such as 'string' for a round cross-section and 'strap' for a flatly rectangular cross-section. Here we use and discuss braid that contains a wide variety of material types and cross-sections. Therefore, we here within use the term *filament* to encompass any material or cross section option, including fiber strings, plastic strapping, composite rods, wooden veneer strips, plant stems, electric power cables, etc. Colloquially, *braid* is typically used only to refer to a few (often three) filaments interwoven to form a solid, narrow cord—such as in hair braids, braided ropes, and kids' arts and crafts.

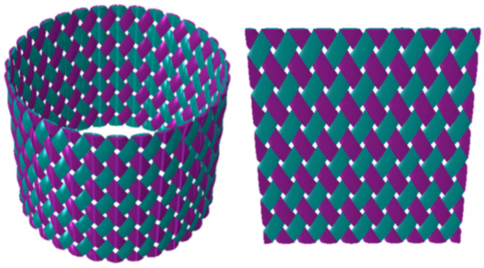
However, as a mathematical, industrial, or technical term, *braid* encompasses a far greater variety of interwoven patterns. The types of braid which we focus on and utilize in this project are often referred to colloquially as *weave*. As technical terms, the distinction between *braid* and *weave* is as follows:



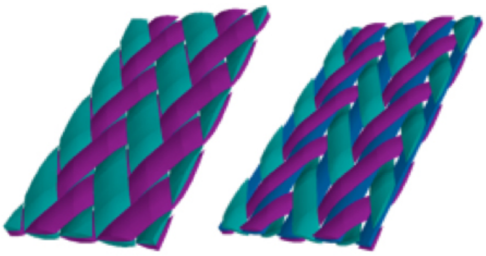
Braid: an organization of interwoven filaments where all filaments perform roughly equivalent functional roles. Filaments might be classed into groups based on their *direction*, but these groups are still of the same type because of their equivalent *function*. The word *equivalent* here is important, because the direction or organization of filaments might mean that their roles in the braid are not exactly the *same*, but are still roughly *equivalent* in terms of their function within the braid.

Weave: an interwoven organization where the filaments are contained in two easily recognized separate functional 'types,' such that the two types perform distinctive functional roles. The two filament types in weave are *warp* (i.e., the filaments that span the full length of the weave and do not change direction) and *weft* (i.e., the filament or filaments that hold the *warp* filaments in place, by weaving through them, then switching direction and weaving back the other way, repetitively).

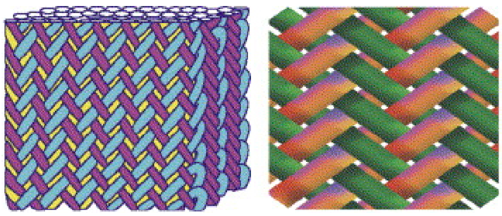
The requirements to be considered *braid* are rather general, and therefore the category of braid is expansive and contains many sub-types. A few of the important sub-types are:



Tubular, flat. Braided filaments can be organized into a braid that is *tubular* (i.e., in a sheet that is continuous, and therefore forms a tube), or into a braid that is *flat* (i.e., in a dicontinuous sheet). *(Image reprinted from [149].)*



Biaxial, triaxial. Braids can contain differing numbers of filament direction groups, mainly forming the sub-types *biaxial* (i.e., with two direction groups) and *triaxial* (i.e., with three direction groups). In biaxial braids, the two direction groups usually oppose each other at an oblique angle, and can be considered symmetrical to each other. In triaxial braids, two of the direction groups are usually the same as one would see in biaxial braid, while the third group usually bisects these first two groups, running parallel to the main axis of the braid overall. When the angle of inclination on triaxial braid filaments changes from the norm, such that all the angles between all three direction groups become equal, it can be difficult to determine whether the organizational category is indeed *braid*. Some technical contexts will refer to this specific type of triaxial organization by other names; here, we will refer to this type as braid. *(Image reprinted from [149].)*



3D, 2D. Braid filaments can be organized in a 2D manner or a 3D manner. In this context, the 2D or 3D designation is mathematical or organizational, of course, rather than a description of how a physical braid takes up space. Therefore, a *tubular* braid, defined above, is a 2D braid, because its filaments form a 2D surface that is periodic along one axis. A 3D braid, by contrast, has filaments crossing in and out of any single 2D surface. 3D braid is often 'solid,' as compared to 2D tubular braid, which has a hollow core. *(Image reprinted from [130].)*

We select braid as our method of construction in *flora robotica* not only because the mechanical properties of braids are well-suited to our application (as detailed throughout the following section), but because it has a generalizability and a flexibility not readily found in most methods of construction (see Fig. 1, and see more details in Sec. 2.3.1).

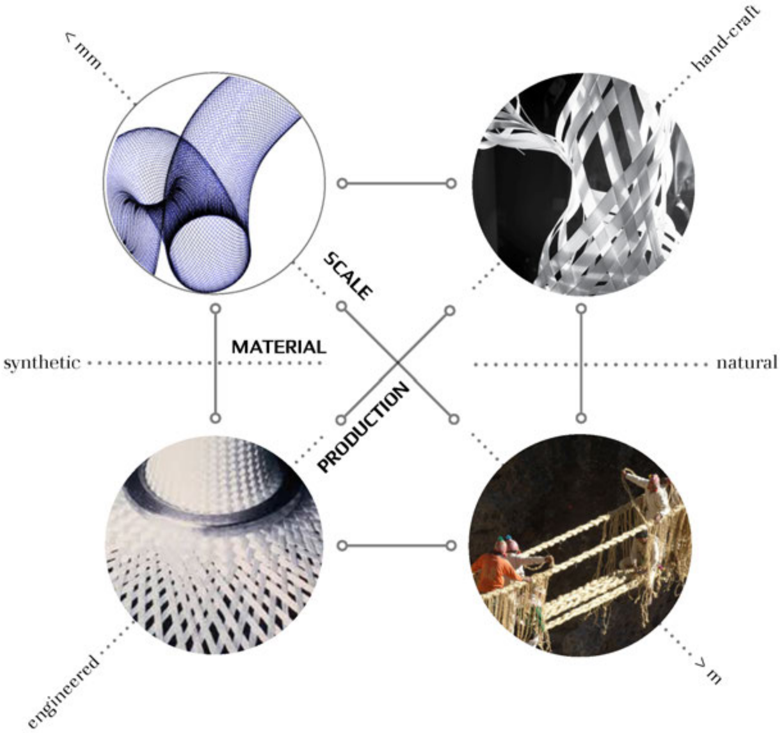


Figure 1: The logic of braid is general across scale, material, and production.

Figure 2: Hand-braiding can be used to extensively explore braid, including braids with highly complex surface topologies.

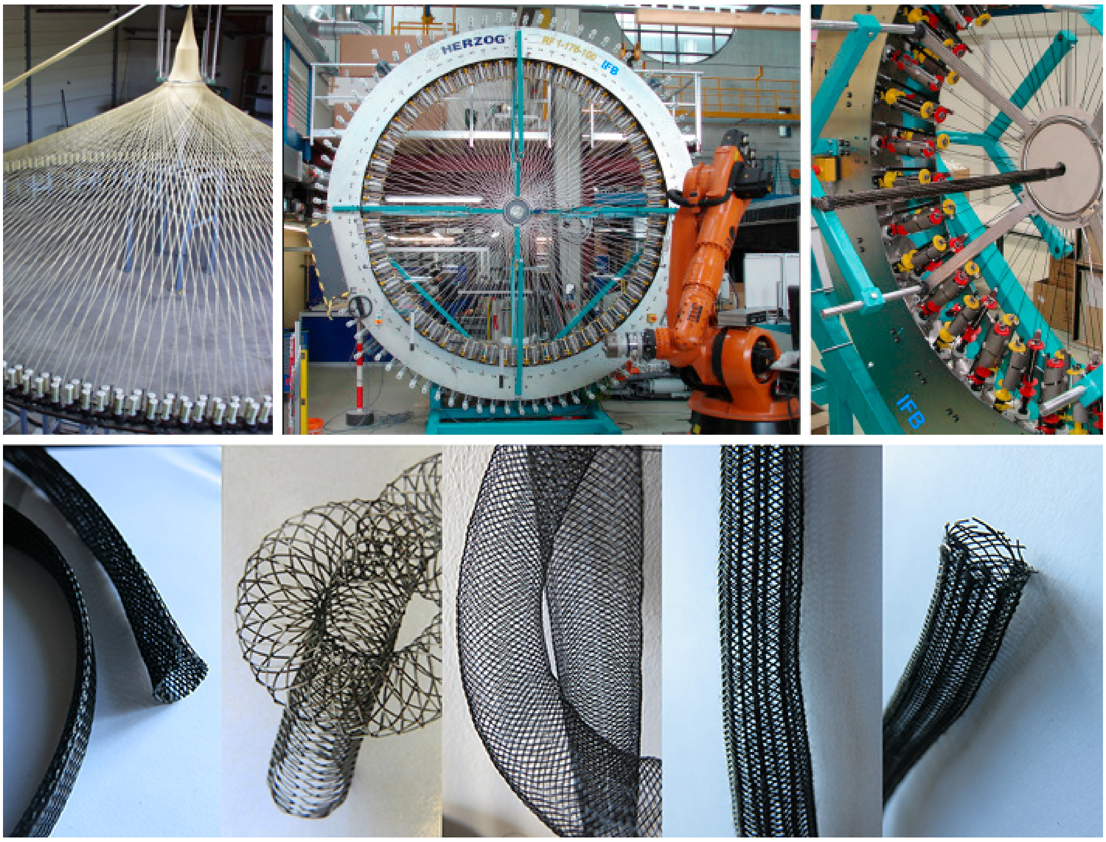


Figure 3: A number of precise braid products (bottom) with various mechanical properties—but typically 2D and tubular—are industrially manufactured (top). *(Top) images reprinted from [130].*

Figure 4: Plants can be braided by artificial process (right) or by natural tendency (left).

Figure 5: Throughout the project, we have found braid to be noticeably user-friendly.

Braid can span material and spatial scale, from microscopic (in health applications) to the size of a building, providing relevant shape properties and mechanical performance across each of these scales. Braid can also span categories of production and application, from highly engineered and industrially produced, to fully hand-crafted and forgivingly resilient to pattern irregularities. Braid can also span a range of materials, from synthetic to natural, refined to rough, fibrous to plastic.

This flexibility is advantageous in the development of the project, as we use every available method to investigate the properties of braid as a method of construction. We use hand-braiding (see Fig. 2) to explore and refine strategies of filament organization leading to novel, topologically complex, and architecturally compelling braided artifacts. We use the foundation of industrial manufacturing's outputs and processes (see Fig. 3) to refine the precision and approach of our braiding techniques, developing our own method for autonomous fabrication that suits the needs of the project (via a distributed braiding machine that is highly reconfigurable due to its modularity, see D1.2 and D1.3).

This flexibility is also advantageous because the project of course includes not only mechanical elements in its constructions, but also integrated electronics (see Sec. 4.2.1) and integrated plants (see Sec. 4.2.2). Braid's flexibility is receptive to many different strategies for mechanical integration of such elements. It is even possible to braid the plants themselves (see Fig. 4).

Beyond the advantageous mechanical properties, and the many relevant flexibilities offered by braid, braid forms very attractive and compelling artifacts (see Sec. 3.1). We have also found, throughout the development of the project, that it is very approachable and friendly for new users, who take to it quickly both in terms of aesthetics and in terms of the fabrication itself. Newly initiated users, with little prior background in the hand-production of intricate artifacts, are able to successfully hand-braid attractive objects with sophisticated surface topologies, on their first day of braiding. These features of braid, while not as relevant for the research development of the project, are highly relevant in the context of the future Social Garden, in which *flora robotica* is meant to produce architectural artifacts that are socially compelling for users, and which inspire interaction and use from the general public.

2.1 Introduction to mechanical properties of braid

Continuous interlacing material is an ancient technique of building. The interlacing organization and continuity of filaments allows braided elements to be self-structuring if filaments are sufficiently stiff. Because individual filaments are not mechanically affixed to one another, they are also able to translate and rotate at intersections. They are mechanically flexible, able to contract and elongate without change to organization of filaments, and able to form a variety of complex shapes. Braid can serve as a universal organizational structure, encompassing all elements of *flora robotica*, from architectural-sized mechanical scaffolds that perform structural roles (and support plants and robots) to electronics-embedded soft-body robot arms that can be actuated and manufactured via distributed hardware.

Figure 6: Filaments in braid can be organized in nearly limitless ways, transitioning between number of filaments, repetitiveness of pattern, dimensionality of organization, and more features, without disrupting the continuity of the contained filaments.

In the below contraction/elongation demonstration of a tubular braid, a cap-end braid of 31 mm polymer strips is compressed to its most contracted state, and is expanded to its most elongated state. In the most contracted state, the braid is 0.4 m in diameter and 0.75 m in height; in the most elongated state, the braid is 0.3 m in diameter and 1.35 m in height (not pictured). The braid can be expanded or contracted without enacting any change on its properties.

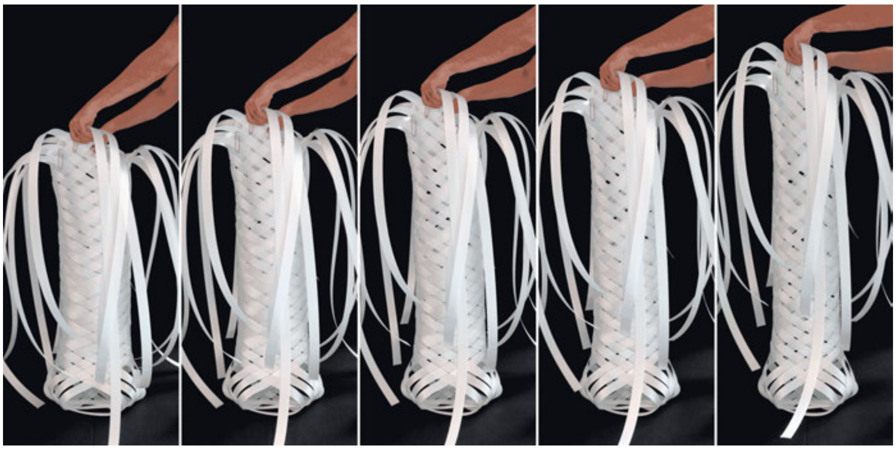


Figure 7: Demonstration of elongation in a capped tubular 2D braid.

Both biaxial and triaxial braid can be organized into a wide variety of continuous surface types. Beyond these standard categories, we also utilize and explore quadaxial braid (i.e., braid with filaments in four direction groups), and braid with even more filament directions (see Fig. 8, left). In any of these categories, if the individual filaments are sufficiently stiff, the angles of filaments within a direction group can be manipulated to create individual cells (i.e., holes) of varying size (see Fig. 8, right). Triaxial, quadaxial, and others can be readily transitioned between within a single braid (see Fig. 8, right, far right), forming *multiaxial* braid. Mulitaxial braid is one of the strategies that allows doubly curved surface geometries in braid (see Fig. 8, far right). From biaxial to multiaxial, braids can sometimes be very pliable. Because structural stiffness is important when building large structures, we investigate methods for increasing the stiffness of braids (see Fig. 8), described in detail throughout the next subsection.

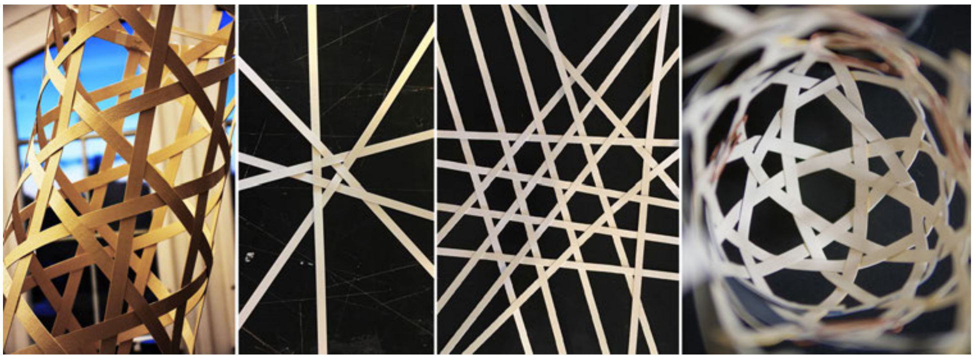


Figure 8: Examples of braids with more than two filament direction groups. (Far left) triaxial tubular braid; (left) a single cell of a flat quintaxial braid; (right) flat triaxial braid, with one cell of quadaxial in the upper right; (far right) multiaxial double-curvature surface braid. *Fabricated in part by Master's of Architecture students from KADK.*

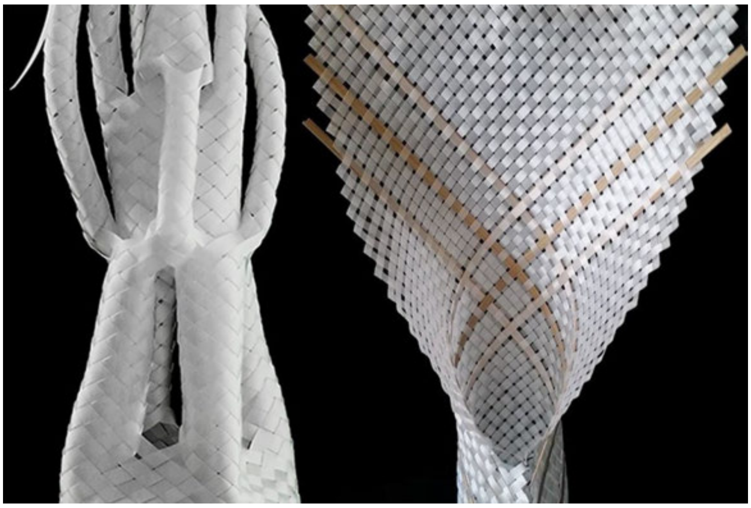
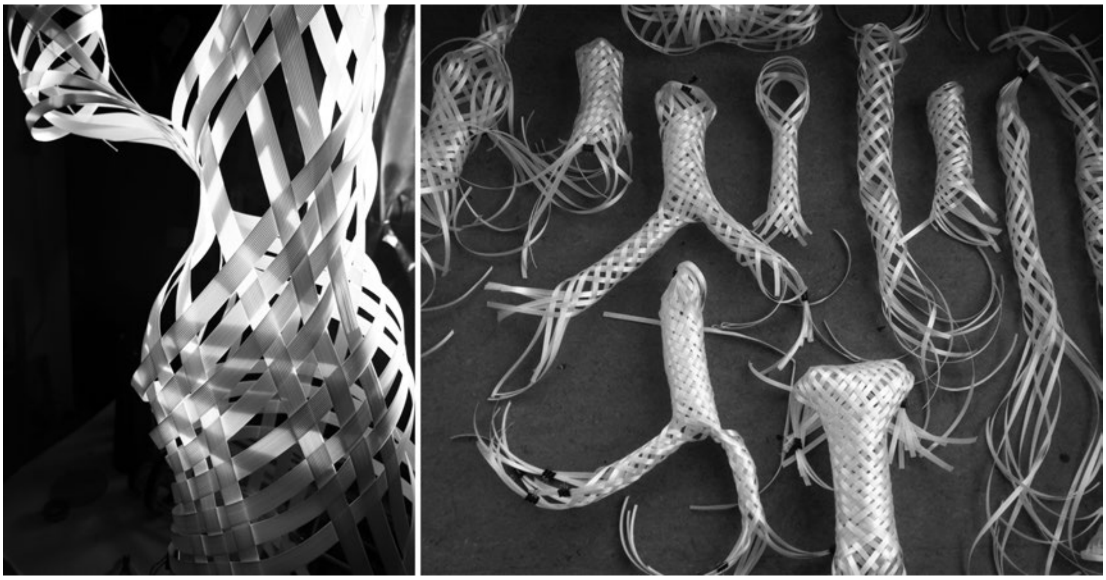


Figure 9: Two of the strategies for stiffening braid. (Right) stiffening by surface geometry, (left) stiffening by filament material.



2.2 Material testing

To explore the array of complex shapes possible with braid, material prototypes were produced using fiber-reinforced plastic strapping laminate, in various widths and stiffnesses. Flexibility of filament organization allows for diversity of braid attributes, especially surface topology features such as branching. Standard 2D tubular braids, while very useful for mass-production in some existing industrial applications, may not offer enough variety in features to accommodate both the functional needs of bio-hybrid structures and the occupational needs of human users in buildings and spaces. To expand the types of structures available, one could make braids of braid, which we investigated using different sizes of industrial braid (see Fig. fig:braid:organizationtests:braided-braid).

Figure 10: Polymer filament tubular braids of differing diameter, braided together.

It was found that further complexity can be achieved by introducing topologically complex features into the braid. The first basic feature that was investigated was bifurcation. Bifurcation was found to be conducive to producing braided structures that can organizationally represent the graph outputs of the VMC controller one-to-one, in cases when this is desired, but also to be useful in more open-ended interpretations of the VMC's output (see "Integrated Growth Projection" in D2.3). Beyond bifurcation, variations in the pattern of interlacing were found to allow transitions between 2D tubular braid and flat 2D braid, transitions that create caps and other features on 2D tubular braids, and transitions inverting a bifurcating 2D tubular braid, such that side of the surface facing inside becomes the side of the surface outside. Many of these topological features, such as the inversion type, are to the best of our knowledge novel features within braid manufacturing research.

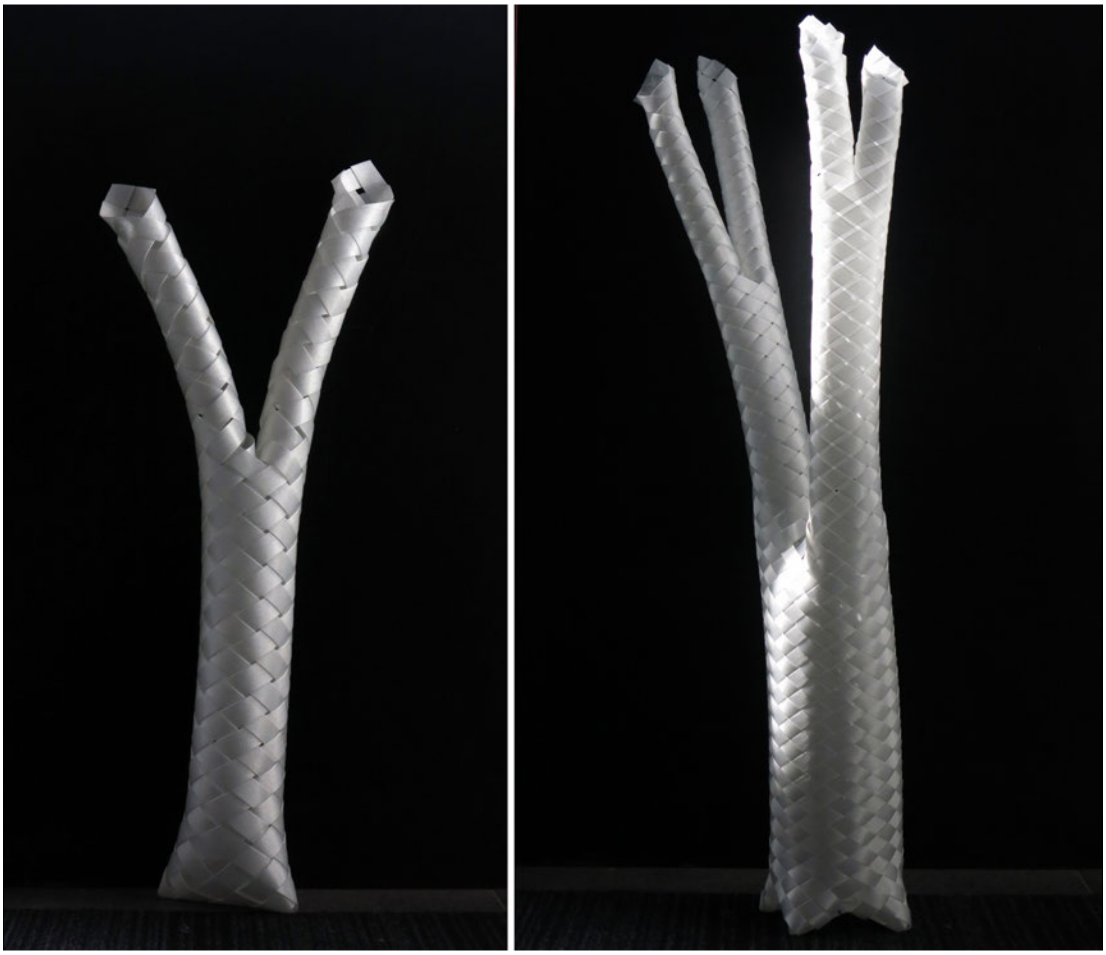


Figure 11: Bifurcations in tubular biaxial braids. (Left) A tubular braid that bifurcates into two new branches; (right) a tubular braid that bifurcates into two new branches, which then bifurcate again, forming four branches in total.

Variations in tubular braid organization were found to produce several simple feature types, which we categorize into not only tube (i.e., open-end tubular braid); but 'cap' (i.e., tubular braid with a square-shaped cap-end,formed by simultaneously rotating the angle of filament directions in the braid); 'cleft' (i.e., a one-sided cap); 'fork' (i.e., bifurcation); and 'graft' (i.e., a bifurcation that incorporates new filaments or inverts their directions). The 'graft' feature type was discovered to lead to very complex surface topologies when used in a braid containing many bifurcations and inversions.

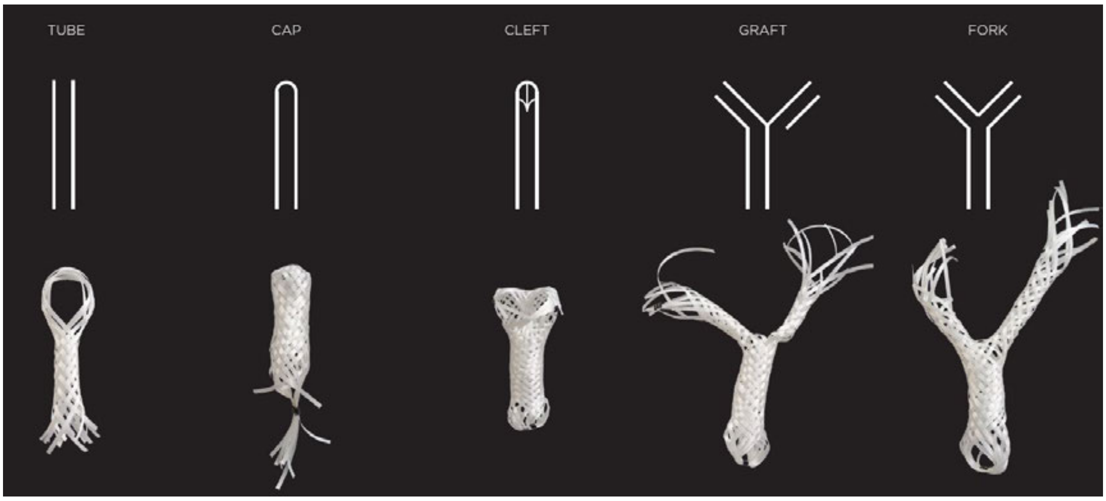


Figure 12: Feature categories of tubular braid. Each category contains varieties based on details of filament organization. Features can be added to any tubular braid, and being 'modular' in a certain way, can be combined to exist simultaneously in any single braid of sufficient organizational complexity. (From left to right) Tube, cap, cleft, graft, fork.

In working toward the objective of analyzing deformations in hand-manufactured braids, and the objective of developing calibrated digital structural models of material braid prototypes, the initial hand-manufactured modules were laser scanned (see Fig. 13), using a FARO Focus3D laser scanner. Further work on a data-driven model of braid mechanics is under ongoing investigation (see Sec. 2.3.2); any relevant results will be reported in D1.4.

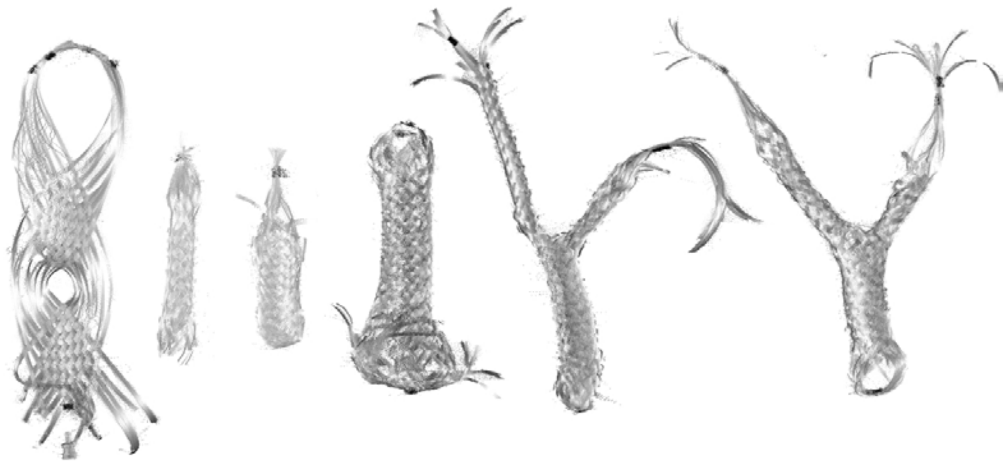


Figure 13: Point cloud 3D models of braid features, produced through laser scanning.

Variations in braid topology and braid tightness that lead to different types of branching were explored in further detail, through continued material testing. These variations include branches with filament direction continuity at tube transition point, branches with reversed filament direction at transition points (see Fig. 14), multi-branching (i.e., a tube branching immediately into more than two branches, instead of bifurcating), and sub-branching (i.e., a branch that branches again).

Figure 14: Some branching types in 2D biaxial tubular braid. (Far left) Bifurcation with both branches displaying filament direction continuity; (left) bifurcation with the lefthand branch displaying continuity and the righthand branch displaying reversed filament directions; (center) bifurcation with both branches displaying revered filament directions; (right) close-up of a branch transition point with reversed filament directions; (far right) a braid with sub-branching.

The prototyping of these braid features and branching types drove the development spatial and geometrical understanding in the architectural vision (described chronologically in Sec. 3.1). The braided scaffold in *flora robotica* however are meant not only as static structures, but as adaptable structures capable of distributed actuation. The flexibility and resiliency of braid is a key advantage in this context (see distributed actuation in D1.3). In working towards the robotic actuation of scaffolds, analog experiments were conducted to explore the actuation opportunities provided by the mechanical properties of braid. Due to filaments not being affixed to one another, but rather being held in place by the surrounding organizational structure, braid filaments are able to translate and rotate at filament intersections, providing opportunities for extensive deformation without the reorganization of material. The elongation and contraction of braid (see above)—which in a tubular 2D braid can occur with radial symmetry or asymmetry around the cross-section—allows standard tubular braid to be actuated like a soft-robot arm (see 3 DOF braided actuator in D1.3). Some additional related opportunities for actuation were explored, through deformation by mechanical stress.

For deformation by mechanical stress, material prototypes were made testing a structured-to-unstructured bending joint (Fig. 15), and enlargement of an opening between filaments, creating a socket (Fig. 16). In the structured-to-unstructured joint, the braid organization at the joints location is structured (i.e., has a regularly repeating pattern) on one side—the upper side of the joint, as shown in Fig. 16—and unstructured (i.e., has an irregular pattern) on the opposing side. The unstructured side of the joint is mechanically less stiff, creating the tendency for the joint to bend in a specific direction.

In the enlarged opening test, the small gap that occurs normally between four filaments in the side of a tubular braid is incrementally expanded—forming a socket—without change to the organizational structure of the filaments. At its largest expansion, the diameter of the opening nears the diameter of the tubular braid (see Fig. 16).

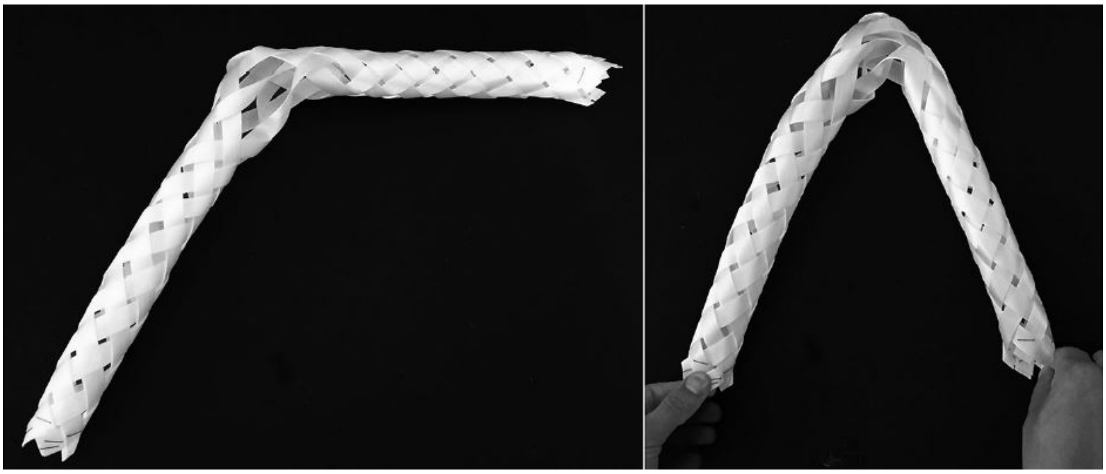


Figure 15: A joint in a biaxial 2D tubular braid, achieved through targeted variation in the filament organizational pattern. (Left) Joint at its resting position, (right) joint manually compressed.

Figure 16: Socket formed in the side of a biaxial 2D tubular braid, through mechanically stressing filaments, without changing the braid organization or cutting any filaments. (Left) The braid without any mechanical stress added; (center) some mechanical stress added to form a socket, to enlarge the space between four neighboring filaments; (right) the socket at its largest possible position, without changing the overall organization of the braid.

Other types of actuation were also explored, with analog experiments meant to investigate the mechanical properties of braid (see Sec. 4.2.1). Material prototypes were additionally used to investigate the steering of mechanical properties of braids, specifically the property of stiffness. Those tests are described below.

2.2.1. Stiffening by material

An unreinforced 2D biaxial flat braid, made from filaments of flexible polymer strapping, has very little structural stiffness. The only way that this type of braid can stand erect is by reinforcement. In some of the early experiments with braids and plants, a trellis for climbing plants is formed by supporting a floppy flat braid with a metal scaffolding rig (see Fig. 17). In this situation, the metal scaffolding is not part of the braid at all, but is rather an external structural element off which a non-structural braid is hung. In this section, we describe our investigations into ways to instead *integrate* this type of support directly into the braid as filaments, such that the braid itself becomes the primary structural element.

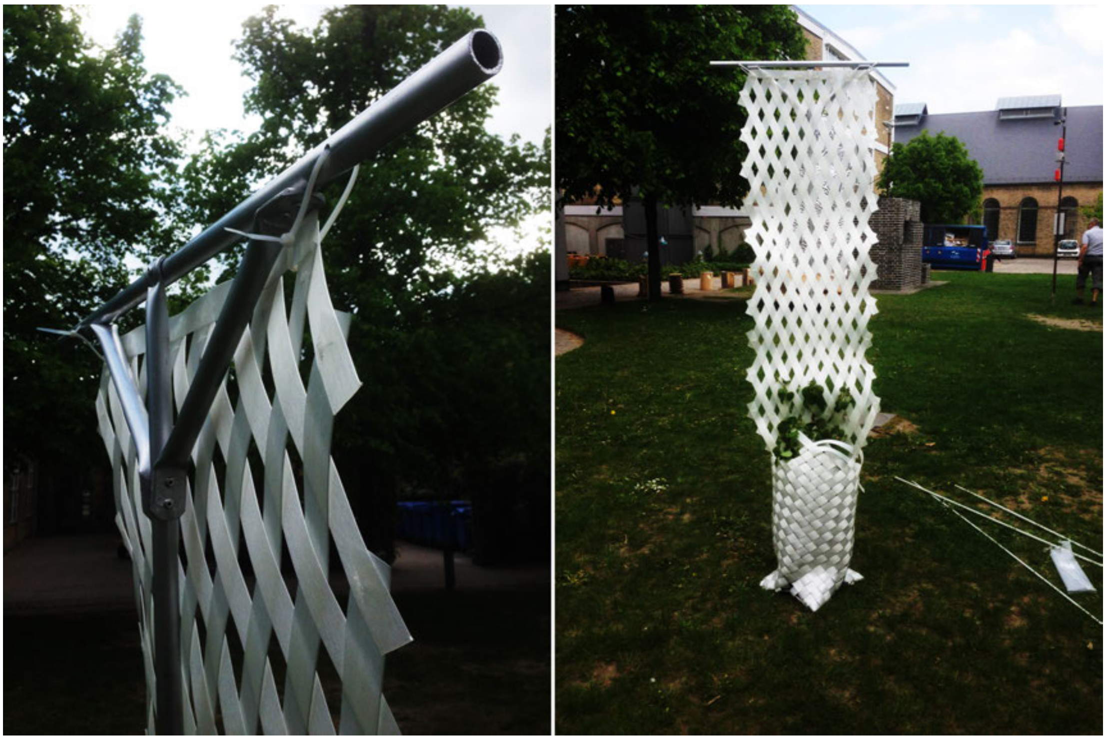


Figure 17: 2D biaxial tubular braid with a cap-end, transitioned into a 2D flat braid, which is hung off a metal scaffolding rig because it is unable to support itself.

The steering of mechanical properties through material was investigated by locally embedding mechanically stiffer filaments into a less-stiff braid. A 2D biaxial flat braid of polymer strips—the same type of braid as the one above, with needed the support of an external metal rig—is stiffened internally via reinforcement, replacing some of the polymer strips with strips of wood veneer (see Fig. 18). Even though the stiffer filaments are only local (i.e. only occurring in a few places, not in a regular pattern throughout the braid), the successfully increase the stiffness of the entire braid. The difference in stiffness between this reinforced flat braid, and the unreinforced one above, is substantial and easy to observe.

In addition to this test of local reinforcement, we also investigated the global use of stiffer filament materials, both alone and in combination with the flexible polymer strips. We tested several types of material: 1) stiffer polymer strips made of polyvinyl chloride (PVC), with a rectangular cross-section; 2) Glass Fiber Reinforced Plastic (GFRP) rods, with a circular cross-section; 3) single-ply wooden veneer strips, with a rectangular cross-section; and 4) half-split mature dried bamboo shoots, with a U-shaped cross-section.

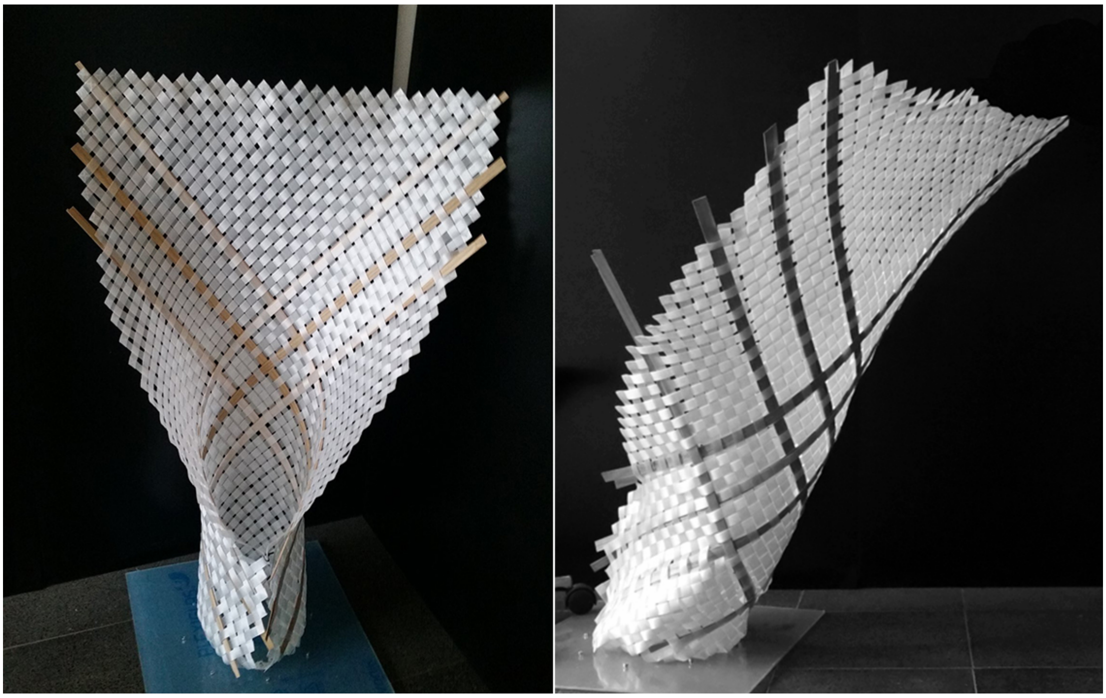


Figure 18: 2D biaxial flat braid of polymer strips, locally reinforced in eight locations, where polymer strips are replaced by wood veneer strips.

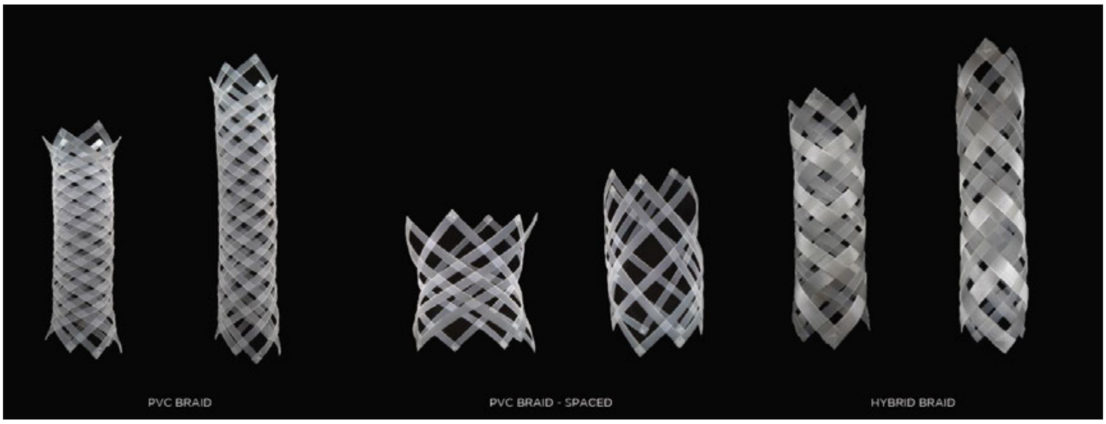


Figure 19: 2D biaxial tubular braid with PVC strips. (From left to right) A tight braid of only PVC strips, in its most condensed resting position; the same in its most elongated resting position; a looser braid of only PVC strips, in its most condensed resting position; the same in its most elongated resting position; A tight braid of alternating PVC strips and flexible polymer strips, in its most condensed resting position; the same in its most elongated resting position.

The stiffer type of polymer strip—polyvinyl chloride (PVC)—is tested both as the only material in use (see Fig. 19, left, center), and as a global reinforcement of the flexible polymer strips implemented in an alternating pattern (see Fig. 19, right). In this early test, it is observed that, in addition to the stiffer filament material lending more stiffness to the overall braid, it also increases the friction occuring between filaments where they collide, allowing more elongation state of the braid to 'hold' as a resting position (see Fig. 19). Mechanical stress applied to the braid to contract or elongate it will then keep it in a more contracted or elongated resting state, with the degree of resting contraction or elongation depending on the stiffness of the filament material and on the tightness of the braid.

Glass Fiber Reinforced Plastic (GFRP) rods are also investigated. They have substantially more stiffness than the PVC strips, but also tend to cause less friction at filament collisions, due to the shape and size of the rod cross-section. GFRP rods are tested by integrating them as filaments in several different ways. A biaxial braid of polymer strips is globally reinforced by also introducing GFRP rods at every filament location, such that a GFRP rod follows the path of each flexible polymer strip precisely (see Fig. 20, top). A biaxial braid is also globally reinforced by alternating between flexible polymer strips and GFRP rods (see Fig. 20, bottom). In this particular filament organization, it is also possible to add additional stiffening at the GFRP-GFRP intersections as seen in Fig. 20, bottom (see Sec. 2.2.3 for details on stiffening at filament intersections).

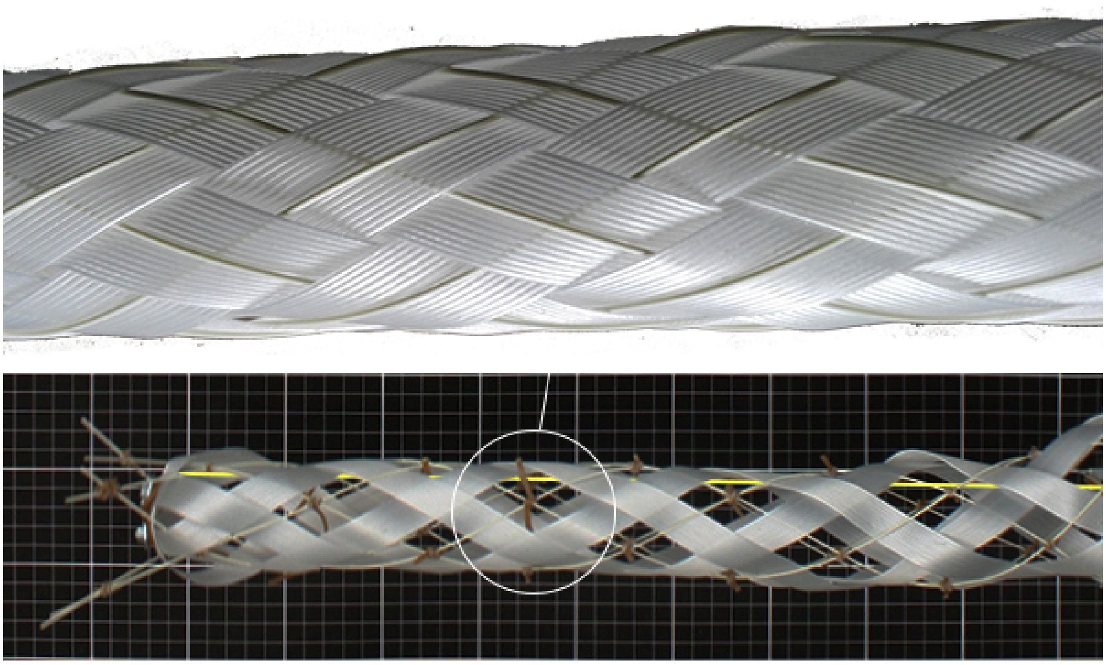


Figure 20: 2D biaxial tubular braids of flexible polymer straps, reinforced globally with GFRP rods. (Top) GFRP rods braided in along with each polymer strap, (bottom) GFRP rods braided in a regular alternating pattern with the polymer straps (also incorporating intersection stiffening technique, see Sec. 2.2.3).

GFRP rods are also tested as the sole filament in a braid, but the high stiffness coupled with the small, circular cross-section results—unless there are a very large quantity of filaments—in biaxial tubular braids that are very narrow, with little to no hollow core (see Fig. 20, left). Such a configuration is not very helpful in terms of increasing the overall stiffness of a braid, as the very narrow resulting cross-section of the braid tube will cause it to buckle much more easily under compressive mechanical stress than a large cross-sectioned hollow-core braid tube of the same filament material. Furthermore, because of their narrow and round cross-section, the GFRP rods in particular perform better loaded in compression along their axes, instead of obliquely to them (as occurs when the GFRP rods are biaxially braided). Therefore, we test GFRP rods as the filament direction group parallel to the overall tube axis, in a triaxial tubular braid (see Fig. 20, right). The filaments on the other two directions in this test are PVC strips. Using the GFRP rods as the vertical filaments in a trixial braid otherwise comprised of filaments with a wide, flat, rectangular cross-section results in a substantially stiffer braid than biaxial ones comprised only of the GFRP rods or PVC strips. As a further advantage, this GFRP-PVC triaxial composite displays a substantially increased degree of friction at filament collisions. This results in a braid that can maintain very large openings between filaments in a resting position (see Fig. 22, center), which is a feature conducive to plant growth (see Sec. 4.2.2). Furthermore, this increased friction at collisions allows the braid to assume resting positions at nearly any contraction or elongation condition, meaning that mechanical stress to contract or elongate the braid need be applied only once to actuate the position, rather than continuously to maintain it (see Fig. 23).

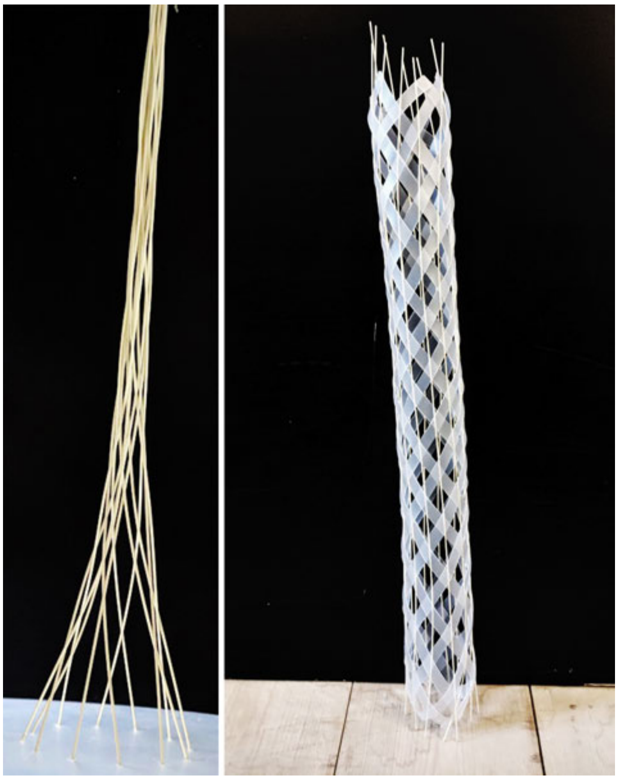


Figure 21: 2D tubular braids incorporating GFRP rods. (Left) Biaxial braid comprised solely of GFRP rods, with ends anchored in a wide circle; (right) triaxial braid with PVC strips on the two biaxial directions, and GFRP rods on the third, vertical direction.

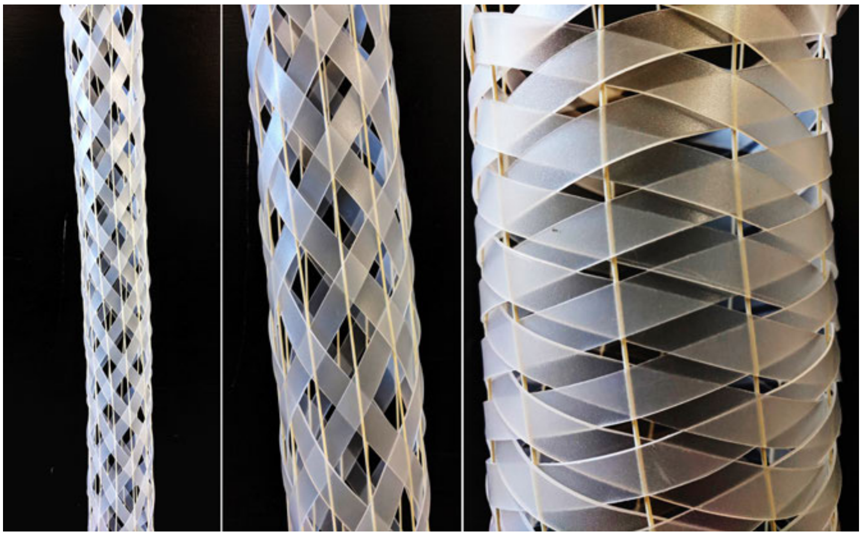


Figure 22: 2D tubular GFRP-PVC composite triaxial braid. (Left) elongated postion, (center) close-up on elongated position, (right) contracted position.

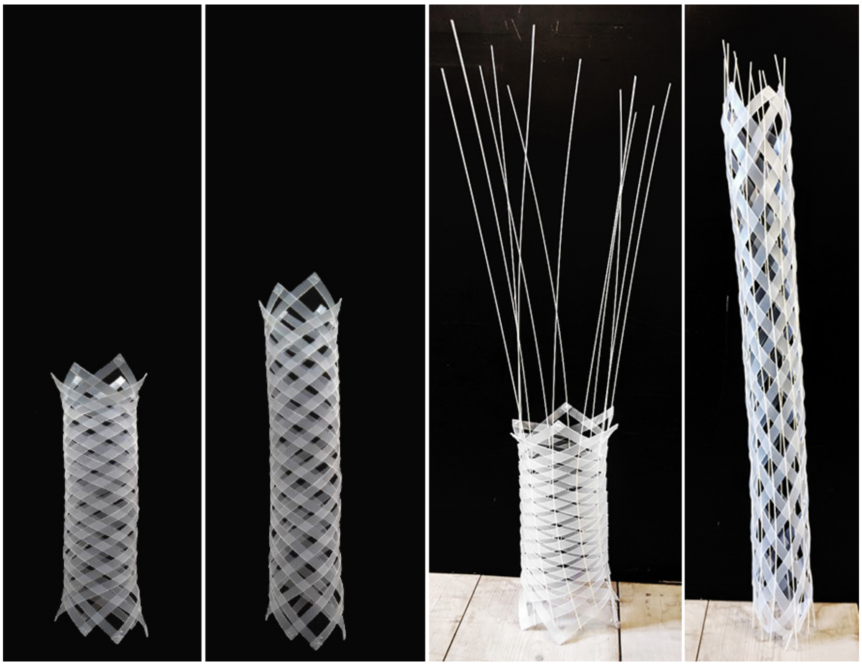


Figure 23: 2D tubular PVC biaxial braid (left), compared to the exact same braid, but with GFRP rods added in the triaxial direction (right). The PVC biaxial braid will maintain less extreme resting positions, especially in terms of elongation, than its GFRP-PVC composite triaxial counterpart—the difference in range is very substantial. (From left to right) Most contracted resting state of the PVC biaxial braid; the same braid in most elongated resting state; most contracted resting state of the GFRP-PVC composite triaxial braid; the same braid in its most elongated resting state.

Figure 24: (Left) Single-ply wood veneer strips as filament material; (right) close-up of the wood veneer used in a triaxial braid. *Fabricated in part by Master's of Architecture students from KADK.*

Figure 25: 2D biaxial tubular braids incorporating wood veneer. (Left) Braid comprised of only wood veneer; (center) braid of flexible polymer straps with wood veneer overlaid on each strap; (right) a failure point on the wood veneer.

Single-ply wooden veneer strips (see Fig. 24) are also investigated, both as the sole filament material and as a reinforcement to flexible polymer strips (see Fig. 25). Wood veneer, though significantly more stiff than the flexible polymer strips, is also significantly more brittle and therefore goes into failure at a much less tight bending radius (see example of failure point, Fig 25). An advantage of combining the polymer strips and wood veneer into one braid is that they can perform different roles. The wood veneer can lend structural stiffness to the braid, while the polymer strips help increase resiliency by holding the rest of the braid in place if there is a local failure point in the wood veneer.

Figure 26: 2D biaxial tubular braid of wood veneer, with smallest possible tube radius.

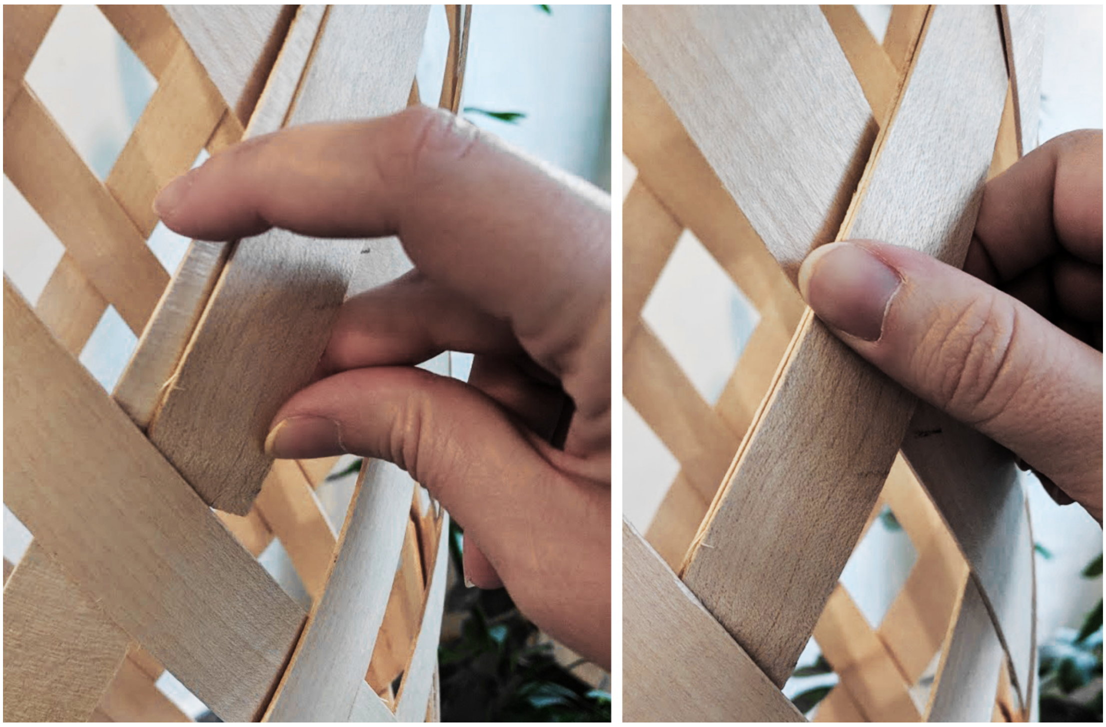


Figure 27: The length limitations of wood veneer are managed by overlapping individual pieces within the braid, to in effect form what behaves as a single filament, as long as the mechanical stress on the braid is not extreme. If increased mechanical stress will occur, overlapping ends of wood veneer can be fastened.

Figure 28: High degree of stiffness allows wood veneer to be used to construct complex braid surface topologies using triaxial and mulitaxial filament organizations. Such topologies however cannot be machined using the developed fabrication hardware, and therefore can only be produced manually. *Fabricated in part by Master's of Architecture students from KADK.*

The wood veneer is substantially more stiff than the other materials with similar cross-section that were tested so far. It therefore results in braids that can have larger resting-position openings between neighboring filaments, and that have a larger lower-limit on bending radius (see Fig. 26). The stiffness allows wood veneer to easily perform structurally in elements of room-size (see Fig. 26), making it a good candidate for constructing architectural artifacts. The large openings that are possible also make the material advantageous in terms of being susceptible to plant growth (especially climbing plants or plants located inside a tubular braid, see Sec.). Wood veneer is also the first material stiff enough to be used in triaxial and multiaxial braids with complex topological features forming doubly-curved braid surfaces (see Fig. 28).

A possible disadvantage to single-ply wood veneer is that the length it can be manufactured in is limited to only a meter or two, while material like the flexible polymer straps is available in continuous lengths hundreds of meters long. As continuity of filament was one of the key features of braid that drove its selection in the project, it is important to be able to join two strip ends of wood veneer together, to form a continuous filament. However, if fabrication automation is to be used, it is also important that this joining approach not place severe limitation on the storage of the wood veneer. Therefore, we extend the length of an individual wood veneer filament by overlapping two pieces of veneer enough that the overlap spans at least two rows of filament in the opposing direction (see Fig. 27). This overlap technique is fairly stable in the wood veneer material without any further fastening, due to the moderate stiffness of the material and the textured, flat surface that allows a high degree of friction at filament collisions.

The final material tested is dried bamboo, split-cut into U-shaped cross-sections (see Fig. 29). It is by far the stiffest material tested here. It is too stiff to be machined into braids by the current hardware of the braid machine, because more force is required to bend this bamboo than would be possible in the current implementation of the machine (see D1.3). However, we still test it for its ability to be used via manual braiding, and because the very high degree of stiffness is very applicable to large-sized structures. We show that it is feasible to braid with material that is this stiff (see Fig. 30)—and therefore also structurally useful for large-seize, even multi-story structures. Furthermore, in principle, a different implementation of the same braid machine could apply the amount of force needed to braid with this stiffness of material.

Figure 29: (Top) dried bamboo; (bottom) close-ups of overlapping ends of split-cut bamboo, fastened together via various strappings. *Fabricated in part by Master's of Architecture students from KADK.*

Figure 30: A triaxial bamboo braid with complex surface topology to achieve a branching of four radially symmetrical 2D tubular triaxial braids. *Fabricated in part by Master's of Architecture students from KADK.*

2.2.2. Stiffening by surface topology and filament organization

That a braid's stiffness can be modified by changing the filament materials is evident; just the precise material type and way of integration must be developed to suit the needs of the project and context. That the braid's stiffness can be modified by geometry is less evidently clear, and to the best of our knowledge this area of project development contains some novel contributions and analyses to the research understanding of braid mechanics.

In 2D biaxial tubular braid bifurcations, the types of branching possible according to filament alignments (filaments with coninuity or with reversed direction; see above), also contain a basic feature of filament organization, which we will call a *cell*. A cell is the continuous gap between neighboring filaments and intersections. Its shape is both an indicator and a control mechanism for overall braid surface geometry. In a standard biaxial braid with a regular pattern, all cells are the same size and shape, each one a square or diamond with four equal sides. However, when biaxial braid surface topology expands in complexity beyond simply flat or tubular, other types of cells are introduced at the points of transition. Even for the simple addition of bifurcations in a 2D tubular braid, this holds true (see Fig. 31). In 2D tubular braid, a bifurcation with two branches both displaying continuity of filament direction will have no interruption in cell types around the majority of the transition, but will contain a single 8-sided cell directly between the two branches (see Fig. 31, center). For branches that display a reversal of filament direction, the transition point will contain two or more 5-sided cells (see Fig. 31, right, left). Thus, we see that small, local changes in filament organization can have drastic effects on overall braid surface topology.

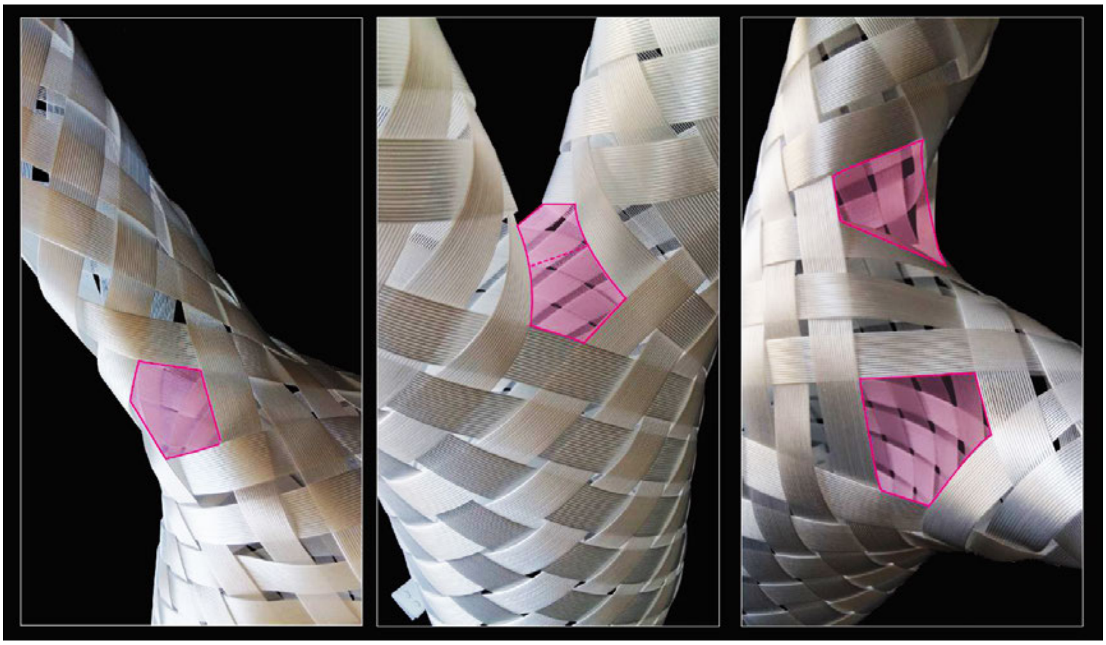


Figure 31: Cell types in bifurcating biaxial 2D tubular braids of polymer straps. Standard condition for simple biaxial braid is all cells being 4-sided. (Right, left) branches with reversal of filament direction, containing 5-sided cells (pink) at the transition points. (Center) branches with continuity in filament direction, containing an 8-sided cell (pink) at the transition point directly between the two branches.

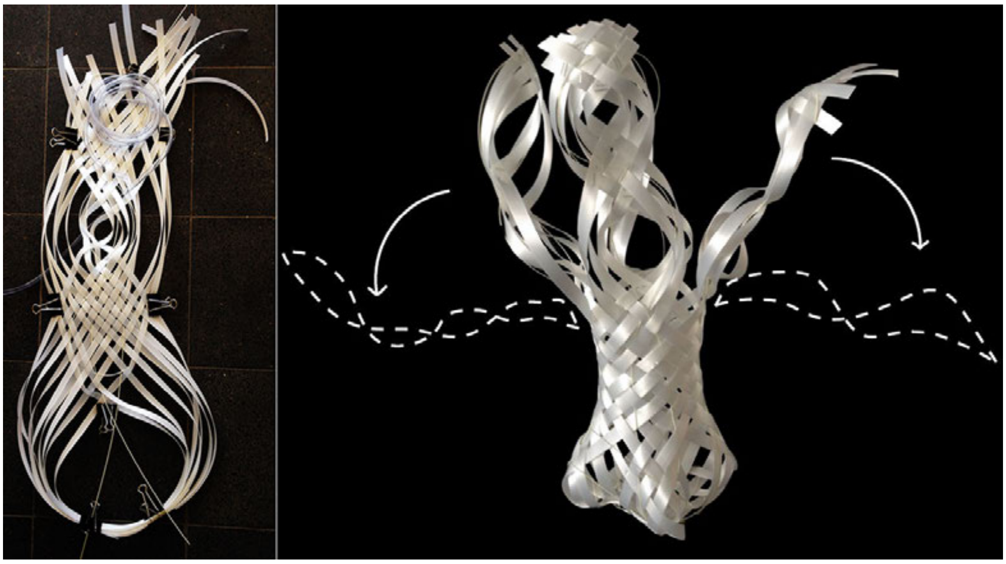


Figure 32: (Left) 2D flat braid transitions to another 2D flat braid, undergoing inversions of individual strips at the point of transition. (Right) Individual strip inversions display mechanical properties conducive to a joint or hinge.

Steering of overall mechanical properties through local filament organization was investigated also by geometrical inversion. The first type of inversion investigated was inversion of individual filaments. This type of inversion can only be completed in braids where filaments have wide, flat, rectangular cross-sections. This was first tested in a biaxial braid pattern where all filaments simultaneously exit the biaxial braid, individual invert (i.e., flip over so the side that was previously 'down' is now 'up' and vice-versa), then re-enter a biaxial pattern again. This inversion type can be seen occurring between two flat braids (see Fig. 32, left), and from a tubular braid, inverting while branching into flat braids, and then inverting to flat braids again (see Fig. 32, right). This second type, where the strip inversion occurs at a bifurcation event that also transitions from tubular to flat, is a complex braid feature that results in branches that are quite flexible at their transition, making them easily and extensively actuated under mechanical stress (see Fig. 32, right). The second type of inversion investigated was inversion of a whole 2D braided surface—that is, not filaments flipping sides individual, but rather filaments flipping in unison, as part of a single 2D braid. This feature type is investigated as a transition from 2D tubular braid to 2D flat braid (see Fig. 33). There, three 2D biaxial tubular braids of varying sizes simultaneously undergo inversion of the braid surface on the side of their tube that is closest in proximity to the other two tubes. These neighboring braid surfaces are transitioned into a single 2D biaxial flat braid. The remaining filaments—those on the opposing sides of each tube—are individually transitioned into the new 2D flat braid situated between the three tubes (see Fig. 33). In this example of inversion, there is a transition from stiffer tubular braid to less stiff flat braid. The weakest point in the braid is the point of transition and inversion.

An important variation on inversion of braid surface was discovered in the development of surface inversions transitioning from tubular to tubular, rather than tubular to flat (see Fig. 34). This specific type of inversion was found to lend a high degree of added stiffness to the overall braid. It was simultaneously found that a tubular braid displaying many complex features of bifurcations and mergers (see Fig. 34) was substantially more stiff than a simple tubular braid of

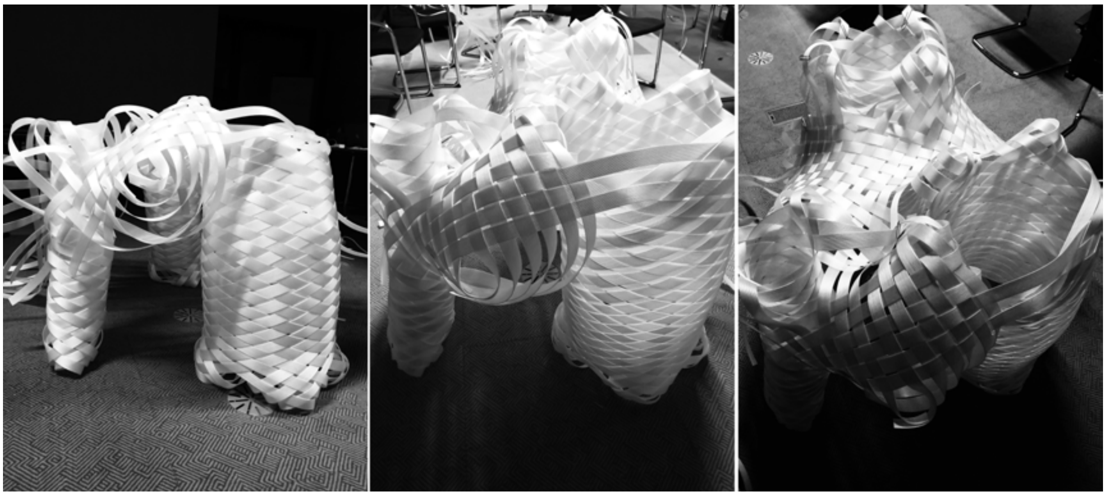


Figure 33: Three tubular braids which undergo braid surface inversion, joining in a central flat braid.

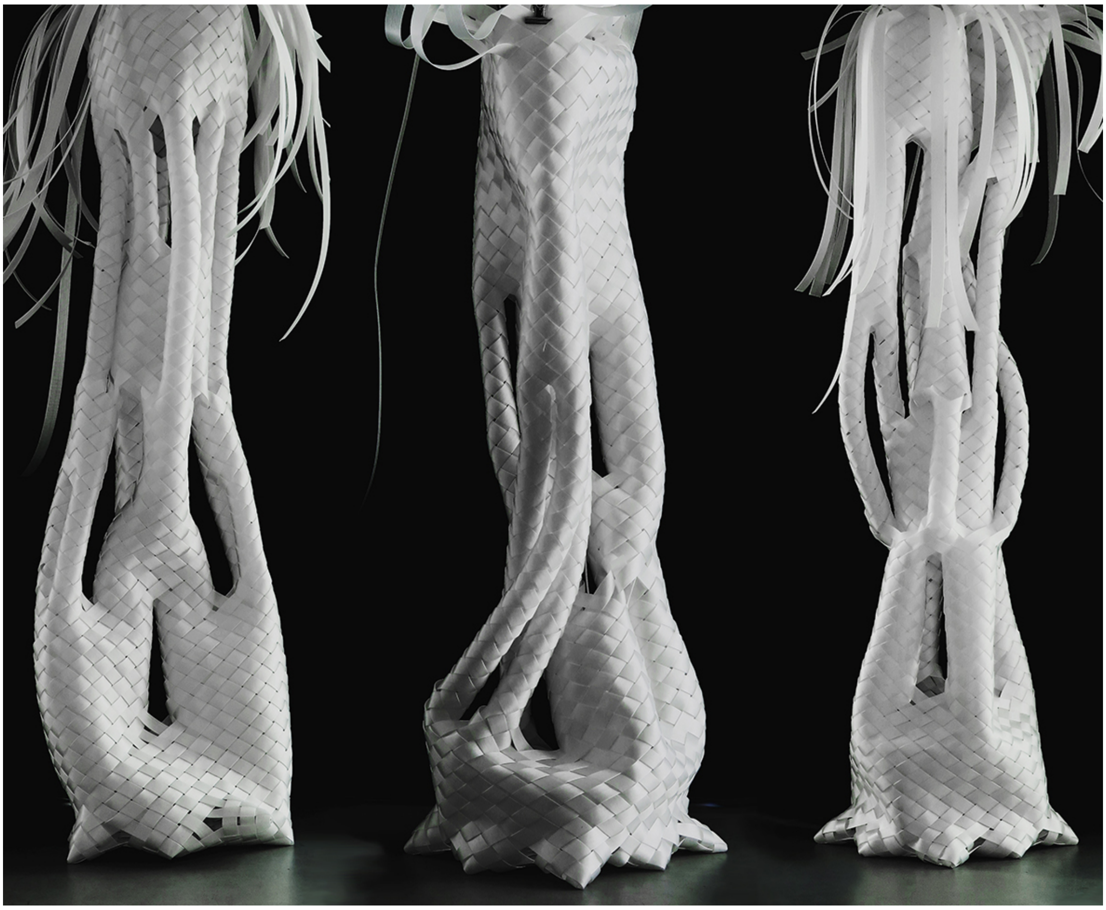


Figure 34: Three examples of braids with highly complex surface topologies.

the same size and number of filaments. For example, the braid to the right Fig. 34 displays both inversions and complexity in bifurcation-merger relationships. This 2D biaxial tubular braid is branched into four equal tubular braids. At this transition, no inversion occurs. Higher up in a second transition, half of the filaments in those four braid tubes are combined into one large central braid tube, and half are siphoned off into smaller auxiliary braid tubes. In this second transition, for the filaments that join the large central braid tube, each filaments geometric relationship to its braid is inverted, and the inversion of each filament occurs in unison rather than individually. The interior side of each filament in the four small braid tubes becomes the exterior side of a filament in the single large braid tube. The braid columns mechanical stiffness is increased by this geometrical inversion.

The steering of mechanical properties through local filament organization was additionally investigated through the relative stiffnesses of structured and unstructured braids (above, see Fig. 15). A tubular braid follows a fully structured pattern for many courses, then follows a partially unstructured pattern for one course, then returns to a fully structured pattern for many courses. The portion of braid that is partially unstructured is significantly less stiff than the portions that are fully structured. The relative mechanical stiffness of these portions creates a soft joint in the tubular braid.

Overall, braid can be considered as a flat-to-form fabrication process, in which the organization of the filaments defines the form. This mechanical feature of braid is well demonstrated in Fig. 35, where a 2D triaxial flat braid lies on the floor in a planar condition, in front of an erect braid which in part contains that same type of 2D triaxial flat braid, but in which—because of the organization of the filaments—this flat braid is not sitting in a planar condition, but rather is sitting in its unsupported and unstressed resting position as a doubly curved surface. In this way, some types of braid surface that exhibit double curvature can be produced by the braiding machine (see D1.3), as the braid can first be produced in a planar configuration, and then the filaments can be manually manipulated or autonomously actuated to shape the previously planar braid into a doubly curved surface.

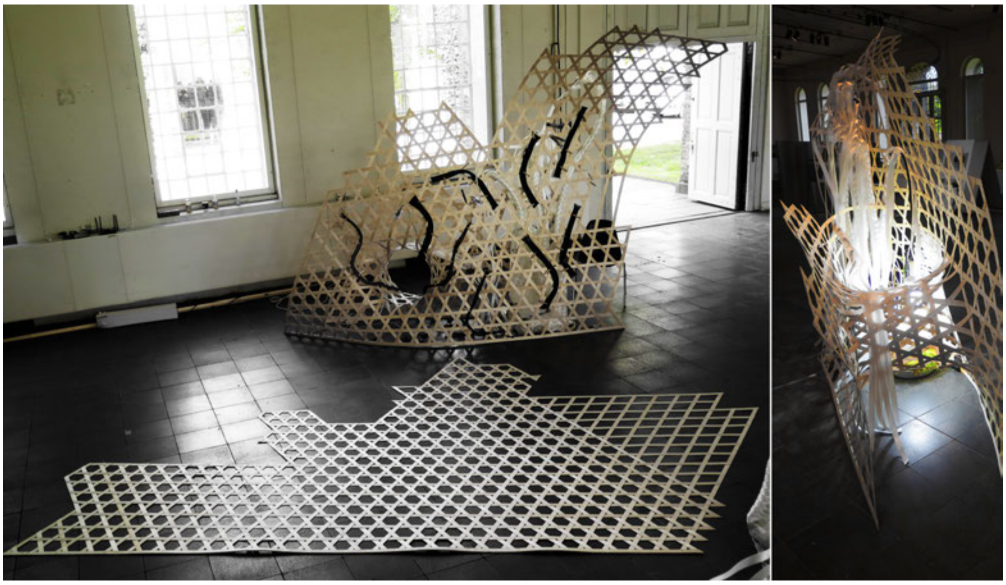


Figure 35: Triaxial braid in the process of going from flat to form.

Above, it was discussed that cells in biaxial braid are normally 4-sided. In triaxial braid, the cell type depend on the quantity of filaments that were added in the triaxial direction. For instance, if one filament is added to bisect each biaxial cell—thereby situating the triaxial filaments such that they share each single intersection point with the existing biaxial intersections—then the new cells in the triaxial braid are all 3-sided. However, if double that quantity of filaments is added to the triaxial direction—such that the triaxial filaments create new intersection points—then two types of cells are present in the triaxial braid. These two cell types are 3-sided and 6-sided, and they are situated in triaxial braid in a regular alternating pattern (see example in Fig. 35).

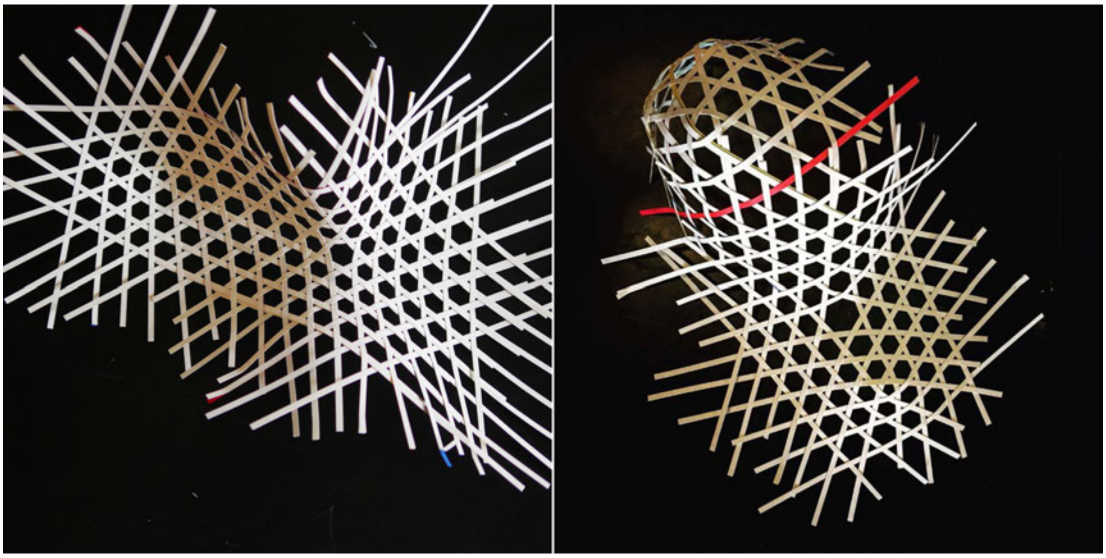


Figure 36: Triaxial braid incorporating irregular cells, resulting in convex or concave features. *Fabricated in part by Master's of Architecture students from KADK.*

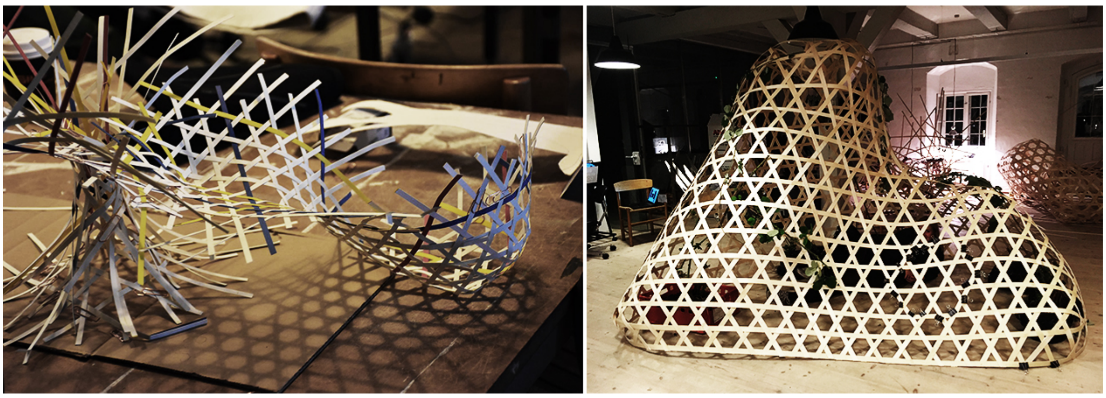


Figure 37: Triaxial braid forming complex surface topologies. In some cases (right) doubly curved surfaces can be achieved without the incorporation of irregular cells. *Fabricated in part by Master's of Architecture students from KADK.*

When new types of cells are integrated into an otherwise regular braid pattern (e.g., cells with side quantity different from 3 or 6, when within a regular triaxial flat braid), complex surface topologies result, often in surfaces of double curvature (see Fig. 36). For example, incorporating a single 7-sided cell will introduce a complex surface inflection point, surrounded by irregular features of surface concavity (see Fig. 36, left: largest sized cell, right: largest sized cell). For a second example, incorporating a smaller cell—one that is 5-sided—will introduce a simple inflection point at the center of surface convexity (see Fig. 36, left: small-to-medium sized cell near the lefthand side of the braid). For a third example, incorporating that same 5-sided cell—not alone, but in a grouping of three cells, in a triangular layout—will also create surface convexity, but will do so by forming an inflection point at each of those three cells, creating a feature combination that resembles something like a dome (see Fig. 36, right: the uppermost portion of the braid, which looks like a three-cornered dome). These cell abnormalities can also be introduced alongside features of filament or braid surface inversion (similar to the inversions described above), to form even more variation in achievable doubly curved surface topologies (see Fig. 37, left).

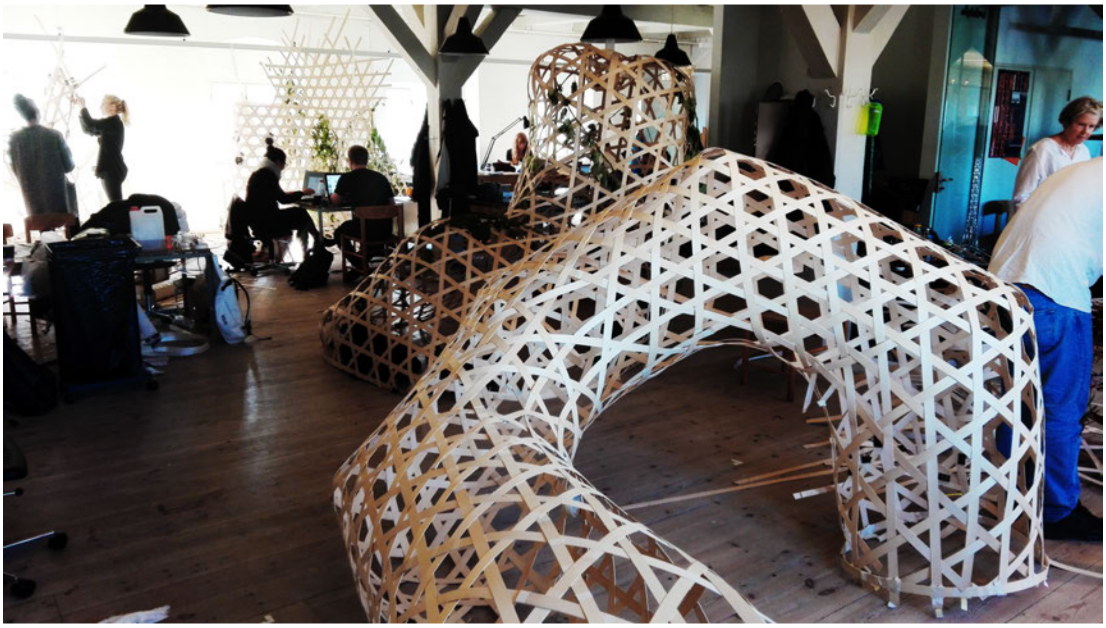


Figure 38: Irregular cells incorporated in a triaxial tubular braid, resulting in complex surface topology. *Fabricated in part by Master's of Architecture students from KADK.*

Complex surface topologies can also be achieved without introducing new cell types, and can therefore be manufactured by the current implementation of the braiding machine (see D1.3). This can be achieved by manipulating the exact size and vertex angles of each cell, without modifying the number of cell sides—quite complex topologies can be achieved using this method, including doubly curved surfaces (see Fig. 38).

Both of these methods—the manipulation of cell size and vertex angle, as well as the introduction of new cell types—are not limited to flat braids, but can be implemented just as well on tubular braid (see Fig. 38). All of the filament and surface manipulations described here serve to greatly expand the possibilities for architectural envisioning, described in Sec. 3.1.

2.2.3. Stiffening by filament intersection fastenings

In some cases, complexity in surface geometry or stiff filament material might not be desired, but increased stiffness may still be. To that end, we also investigate methods to increase stiffening via fastening strategies at filament intersections. This strategy of stiffening sometimes has the added benefit of also increasing the spacing between neighboring filaments when the braid is in its resting positions, which is advantageous for plant growth (see Sec. 4.2.2).

One approach to stiffening via fastenings is to add elastic filaments in the direction opposing the braid's main axis. In a way, this strategy can be considered as the addition of a *weave* element (for weave, see Sec. 2), as the function of this elastic filament is categorically different from the rest of the filaments in the braid, and they could be considered *weft* filaments (for weft, see Sec. 2). In a tubular braid, these elastic filaments can be added around the circumference of the braid tube (see Fig. 39). They could also be added in the same position, but interwoven between the filaments of the braid. That interwoven approach could also be used to add these *wefting* elastic filaments to a flat braid or even a 3D braid (see 3D braid in Sec. 3.3.1).

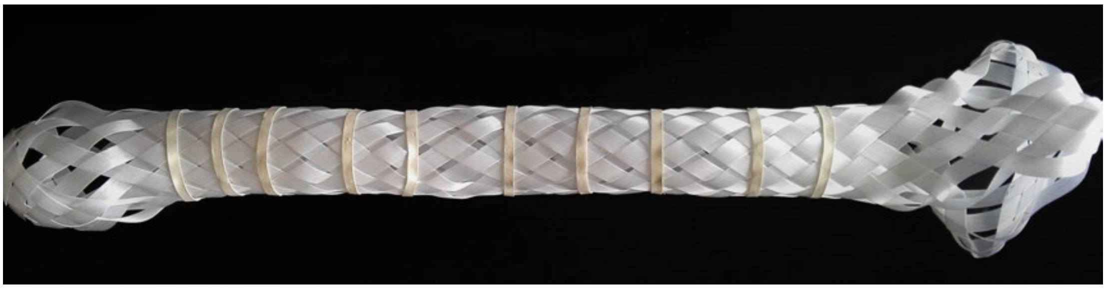


Figure 39: Elastic bands constraining the outer diameter of the braid.

Another approach is to add fasteners directly to each individual filament intersection in the braid. This can be done with elastic ties (see Fig. 40) or with pin joints (see Fig. 41). Both of these fastener types, though constricting the translational behavior of braid filaments, retain their rotational freedom at intersections. As such, the braid can still be actuated effectively in a variety of ways. However, the pin joint style is limited to filament materials that can withstand a hole punched through their center without it splitting or otherwise compromising the material. Therefore, it can be used with material such as the flexible polymer straps or PVC—where the material is poured plastic or at least includes sufficient poured plastic—but cannot be used with primarily fibrous material such as wood veneer or GFRP rods, as the fibers will split apart. As fibrous materials are the stiffest filament materials we currently have to choose from for our braids, the pin joint strategy is not particularly useful. The strategy of using elastic ties, by contrast, is very successful with GFRP rods, of which the narrow and radially symmetrical cross-section furthermore allows a substantial range of motion for actuation. Thus, we use this combination of GFRP rods and elastic bands at individual intersections in our testing of distributed actuation of braid (see the 3 DOF manipulator in D1.3).

The drawback to the elastic band fasteners is that they must be applied manually. The braid they are applied to can be fabricated by the braiding machine (see D1.3), but the fasteners must be applied afterward, which can be a time-consuming manual process if the braids are sufficiently large. Also, the braid machine then needs to be attended during on-site construction in certain intervals, which may be a disadvantage over particularly long artificial growth periods. Furthermore, one of the key properties of braid that drove its selection for the process was the ability for scaffolds to be continuously braided, unbraided, and rebraided. Though this is still

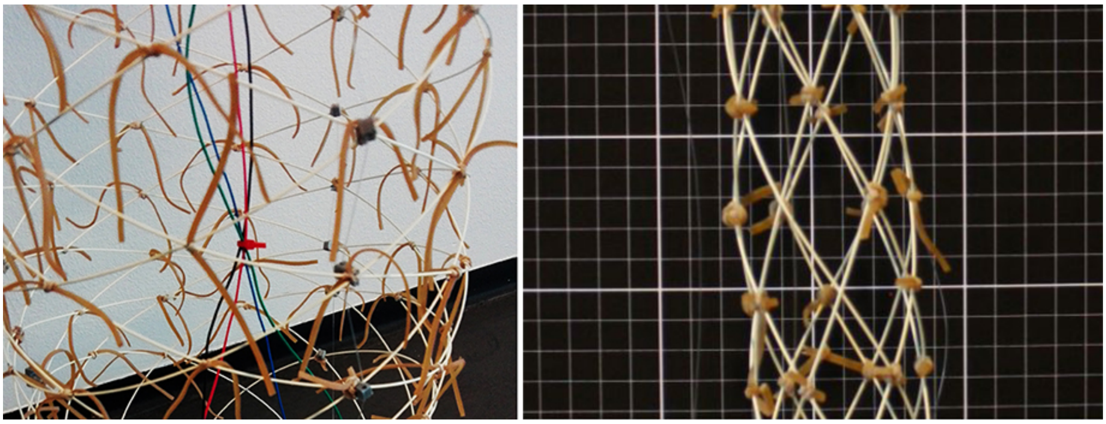


Figure 40: Elastic ties around individual filament intersections.

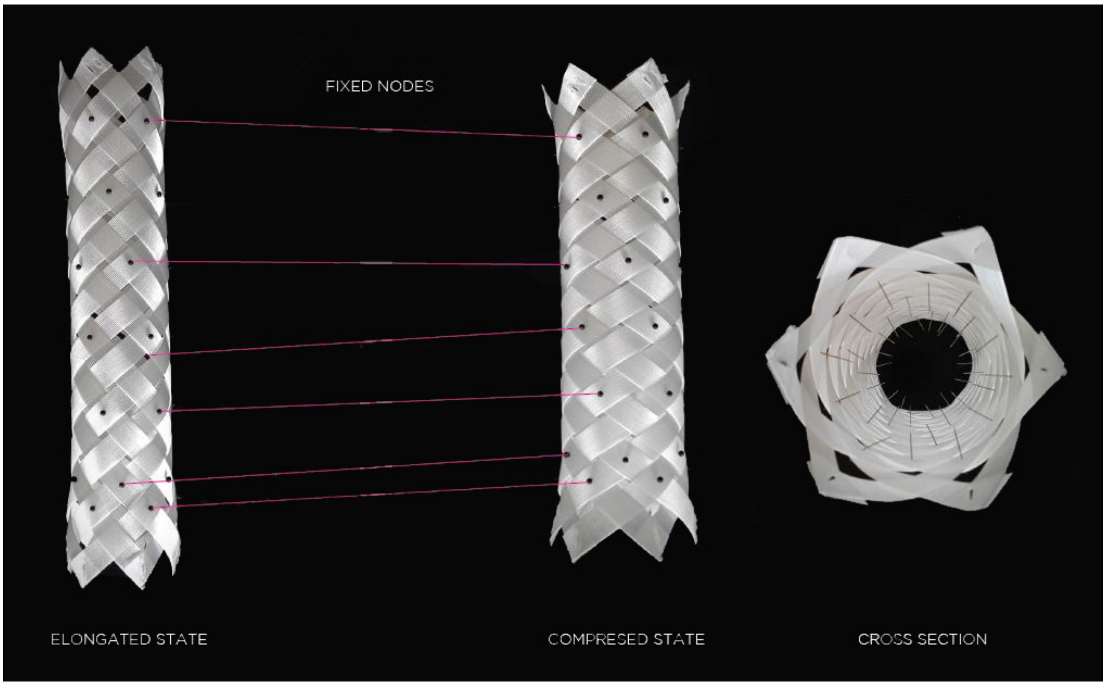


Figure 41: Pin joints through individual filament intersections.

possible with intersection fasteners by manually removing them and reapplying, it poses the same disadvantages for on-site construction and long growth careers. Therefore, we briefly investigate two techniques that instead of using fasteners use exclusively strategies of filament organization that are generalized enough to in principle be used with an extended-hardware version of the braiding machine.

Figure 42: Slotted intersections for stiffening and for enlarging openings.

In one of these two strategies, which can only be used with material having a wide, flat cross-section, a modification is made to the filament material before braiding. The modification is to add center slots at a repeating interval along the length of each filament, and then to pass filaments through these slots when braiding instead of passing them entirely around the whole filament (see Fig. 42). If the length of the slots are at least 200% of the filaments' width, then this technique retains the properties of standard braid, having a similar degree of flexibility in terms of rotation, translation, elongation, and contraction. In order to in principle be manufactured by an extended version of the braid machine, hardware would have to be added to govern the steps of spreading open the slot and passing the filament through. Additionally, the filament cartridges of the braid machine would need to be narrow enough—or the slots would need to be long enough and filament material flexible enough—for the cartridge to be passed through the slot.

In the other strategy—to the best of our knowledge a novel mechanical configuration in the literature—a new functional type of filament is incorporated, in a way resembling the *weft* filament of a *weave*. In this strategy, each biaxially braided filament is paired with a neighbor in its direction group, and the new *weft* filaments are continuously passed back and forth between the two filaments in a pair, binding them together (see Fig. 43). As such, this strategy can be considered a *braid-weave hybrid*. In order to in principle be fabricated by an extended braid machine, new hardware elements would have to be added to manipulate the *weft* filaments.

Figure 43: A braid-weave hybrid.

2.3 Modeling mechanical properties of braid

2.3.1. Braid mechanics literature: Industrial production

Braid technique is based on a principle of oblique interlacing of three or more strands of yarn, filament or strapping [108]. The technique is used to produce artifacts that are larger, stronger, more resilient and, often, more aesthetically charged than the original material. Braid offers tremendous versatility in terms of material, scale of artifact, and method of production. As such, braid is applied across a broad range of industries, including medicine (stents), agriculture (industrial hoses) and leisure equipment (ropes). Braid is also used to produce preforms for advanced composite manufacture [105]. The resulting composites are amongst the lightest yet strongest components currently produced and are utilized in high-performance arenas such as cycling, racing and aeronautics [108]. Despite the versatility, resilience, and scalability demonstrated by braid across many industries and functional uses, it is not a commonly used or discussed technique within contemporary architecture. In parallel to the limited use of braid in architecture, there is also a lack of suitable design modeling tools for freely exploring complex braid topologies against architectural design, analysis, and fabrication considerations. In the work presented here, we concentrate on exploring 2D biaxial tubular braids. Tubular braids offer a rich space of topological freedom, as well as structural potential when approaching architectural scale (see Sec. 2.2.2).

Spatial and topological organization of the bio-hybrid system is steered over time by a combination of high-level design objectives, distributed robot controllers, and user interaction. Achieving this broader goal requires that the braided scaffolds have the ability to reorganize continuously in situ, through a distributed construction process. Such a distributed process may approached by collaborative stationary centrally-controlled braid machines [111], swarms of distributed mobile braiding robots [49], or manual braiding by users. In *flora robotica* we have selected the exclusive use of our distributed braiding machine (described in D1.2 and D1.3). In this context, it has been necessary to develop modeling tools and workflows that can support design speculation and specification, and provide an adequate representation of braid in the context of diverse and often independent design and evaluation tasks (see evaluations in D3.1). To investigate the generalization of the modeling approach, in has been investigated for a number of workflows, including the modeling of complex braids produced by hand, the generation of fabrication instructions for both hand and automated methods, the analysis of mechanical performance of braids, and the adaptive generation of braid morphology.

2.3.2. Data-driven model of braid mechanics

There are many existing models in the literature for braid mechanics, but they are developed for braids that are industrially manufactured for specific applications, and as such are not directly extensible to the braid types used in *flora robotica*, which have different materials, filament organizations, and stiffening methods than any braid types with mechanical models that we found in the literature. For modeling the mechanical properties of our braids, we investigate the possibility of a data-driven model of braid mechanics. Here, we report one possible setup for generating some data from which to build a model. Any developments for a data-driven model of braid mechanics will be presented in further reporting of WP1.

In the setup here (see Fig. 44), a cap-end 2D biaxial tubular braid with alternating filaments of GFRP rods and flexible polymer straps, and with elastic ties at individual filament intersections, is mounted via fixed connections to a stiff mounting plate. This braid contains a combination of several features we consider, discussed in the sections above. If mechanical performance data can be compiled not only for this braid, but for a matrix of braids with different combinations

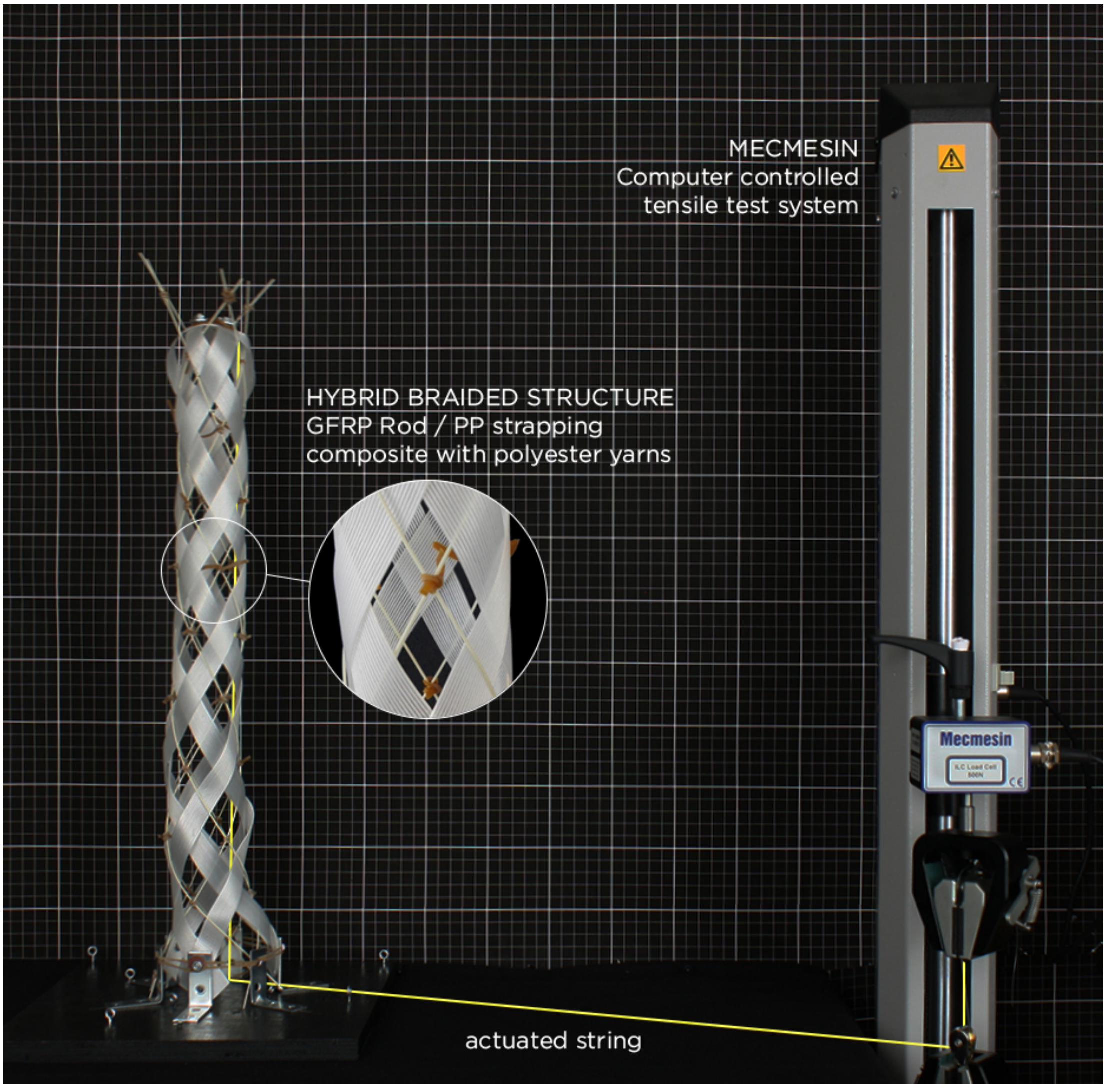


Figure 44: The setup of a tubular braid with actuation string attached to a Mecmesin force tester, for applying controlled loads on the braid.

of features, a data-driven model could be derived or machine learning model could be trained from that data, and could be expected to usefully approximate the mechanical behaviors of our possible braid types, without having to exhaustively measure every possible combination of all our considered braid features.

The example braid is mechanically stressed using a single actuation string of polyester yarn, which is anchored to one side of the braid's top, thread on an unobstructed path through the center of the braid, thread through a fixed socket in the mounting plate, and extended outward to be attached to an actuation device. It is attached to the grip-head (see Fig. 44: grip-head sitting near the base of its actuation axis) of a Mecmesin™ universal computer-controlled force tester, which pulls the string away from the braid as the grip-head moves upward, thereby logging

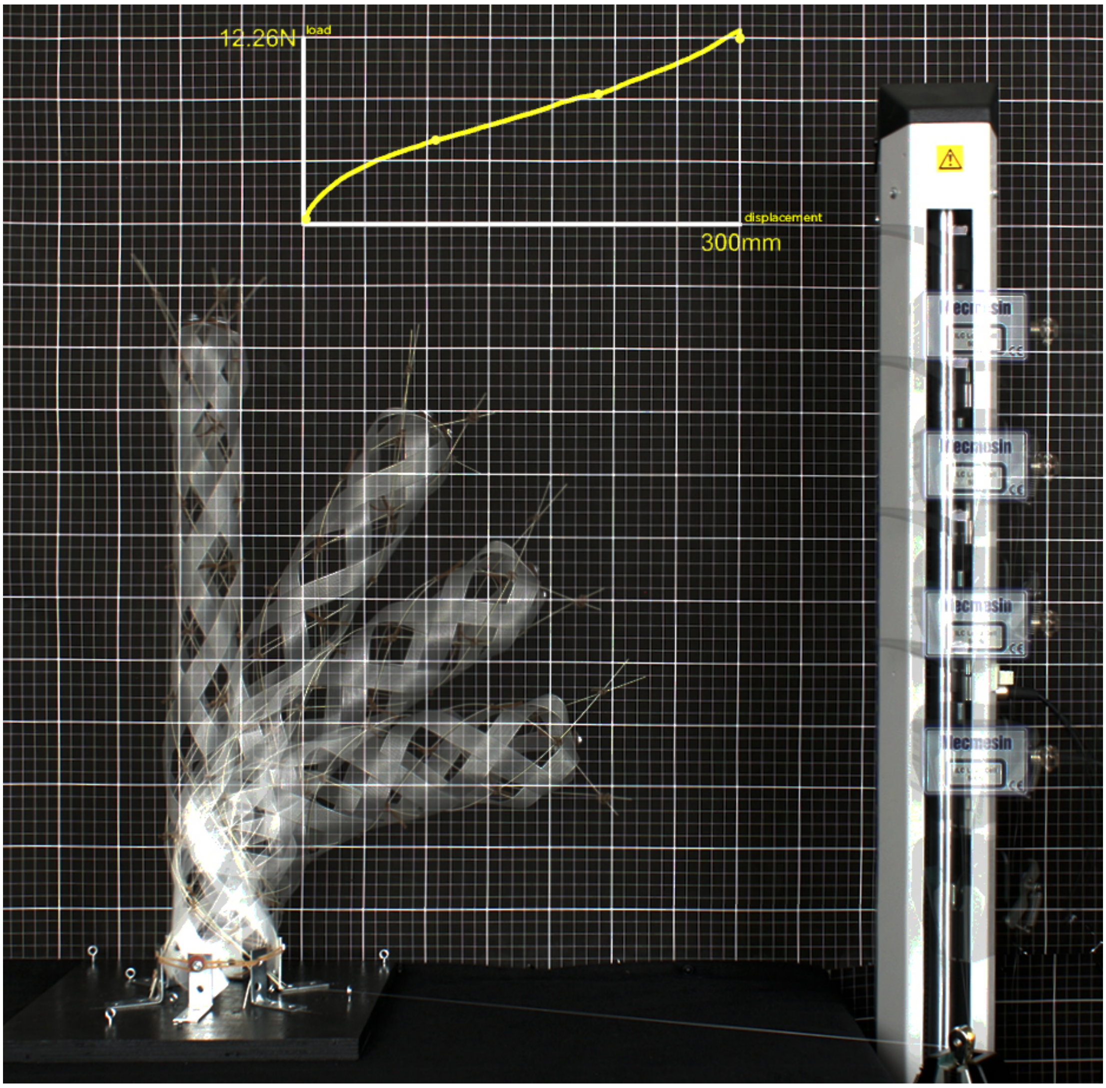
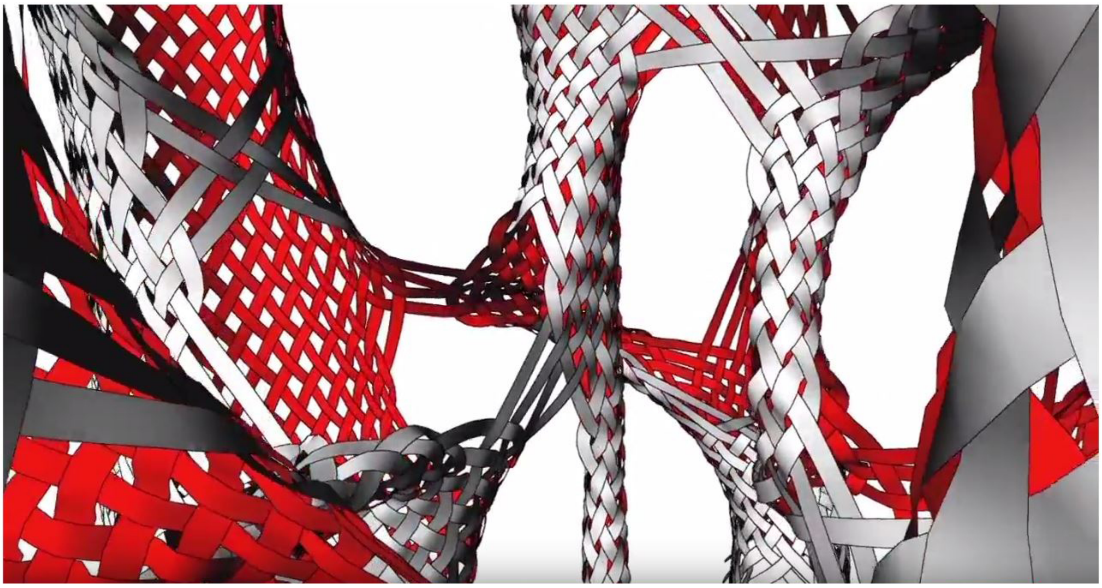


Figure 45: Logged results of the tensile test system setup, with composite photo of some of the measured positions.

the tensile force applied at each timestep (see Fig. 45). Similar force data can be logged with actuation affixed to the braid in different ways, collecting data on different types of mechanical deformation. While the force tester logs the force applied, a computer-vision method is used to log a representation off the braid's deformed shape and positions (see D3.1). The force data combined with the braid shape data could provide the basis for a useful data-driven model of mechanics. A data-driven model could in principle be combined with the physics-based relaxation approach to modeling braid mechanics, described below.



2.3.3. Design tools and work-flows using open-ended physics-based relaxation

We employ our braid pattern and simulation method (described in detail in D3.1) which extends external state-of-the-art in the following ways: by supporting the braid design of both predetermined target shapes and exploratory, generative, or evolved designs; by incorporating material and fabrication constraints generalized for both hand and machine; by providing a greater degree of design agency and supporting real-time modification of braid topologies.

There is a current lack of suitable design modeling tools to support our approach, so we develop modeling tools for our use, supporting multiple design and analysis work-flows. Here we model target geometries, conduct structural analysis, and evaluate the performance and generalizability of the modeling against criteria of geometric similarity and simulation performance.

Braid representation method Here we briefly review our developed braid representation method (see D3.1 for details). In general, the method uses a precomputed set of tiles, which, in their underlying logic, combine different approaches seen in the literature (e.g., [89, 63, 2]). The method works directly on polygon meshes that can be modified in real-time.

The first step in the method is tiling. Following the approach defined by Mercat [89], a predefined tile dictionary provides a complete description of possible braid strip organizations . In the tile dictionary utilized for our standard braid mesh modeling method, there are three possible relationships between neighboring tiles: no connection; connection with two separated strips; connection with two crossing strips. To be able to simulate the physical characteristics of the braiding pattern, it is necessary to translate the tile notation into geometry. The method uses a point grid, with each strip declared as a series of grid-based coordinates on the mesh.

The next step is relaxation. In evaluating the physical properties of the digital model, the braid cannot be approximated to a grid-shell due to torsion occurring in the flat strips. The mesh topology is therefore constructed from triangle meshes with varying density. The constraint-based geometry solver Kangaroo 2 [104] is used to perform relaxation, with objectives to equalize mesh edges, detect collisions for zero length mesh manifolds, and add shell-like behavior. The problem of 'overshooting' may occur when mesh faces are undesirably stretched or compressed by large percentages, so a dynamic constraint incrementally increases initial edge lengths to reach the target. This results in longer calculation time, but achieves tight braids with strips that, if unrolled, approximate the straightness of physical strips.

Design workflows Our method supports at least four example workflows, described throughout this deliverable. In the first workflow (modeling target geometries, described below), we compare our method to existing state-of-the-art approaches by tiling the input of a manually modeled mesh. In the second (generating fabrication instructions, see Sec. 3.3.1), we interpret a model to provide the output of textual instructions for hand braiding. Third (analyzing mechanical properties, described below), we address calibrated simulations for the output of assessing structural performance. Fourth (generative design, see Sec. 3.3.1), we generate braids from the input of the VMC controller for artificial growth (see D2.3). In combination, these workflows show that our braid representation is sufficiently generalized that it is able to both receive multiple inputs (workflow 1 and 4) and be interpreted for multiple outputs (workflow 2 and 3).

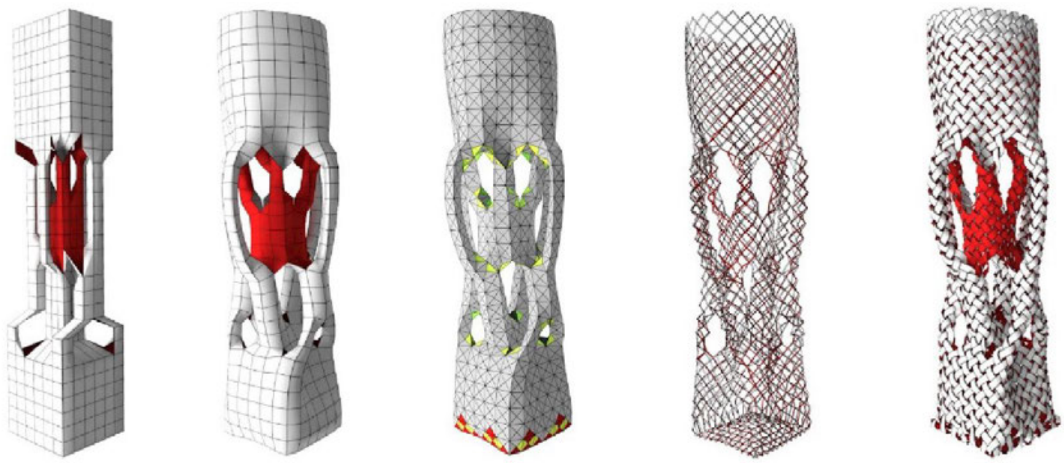


Figure 46: 3D modeling braid typology informed by the hand-braided structures. Modeling steps from left to right are: a) 3D mesh modeling; b) Equalize edge lengths; c) Assign colors to mesh edges; d) Apply tiling; e) Strip-Strip relaxation.

Example workflow: Modeling target geometries In this workflow we demonstrate modeling to predefined design targets, such as those shown in Fig. 46. In these cases, material geometry is a hard constraint that must be considered to ensure an adequate representational approximation. In addition, conforming to local braid conditions such as asymmetric bifurcations (in terms of strip numbers), inversion and 'cornering' displayed by these physical prototypes present further modeling challenges. This workflow has five stages. First, a low-poly quad mesh model is created of the physical prototype. Next, quad mesh edges are equalized by using a custom Kangaroo 2 solver with spherical collision and equal length line constraints in a parallel thread for faster calculation time. Thirdly, all braid conditions are specified by the application of tile colors to the quad mesh. The braid tiles are then applied from the existing tile dictionary (see D3.1). Finally, strip-strip simulation (see Fig. 47) is used to achieve a tight and realistic braid model (see Fig. 48). Within *flora robotica* the making of material tests is an essential mode of exploration, as is the ability to accurately represent these complex surface topologies once produced.

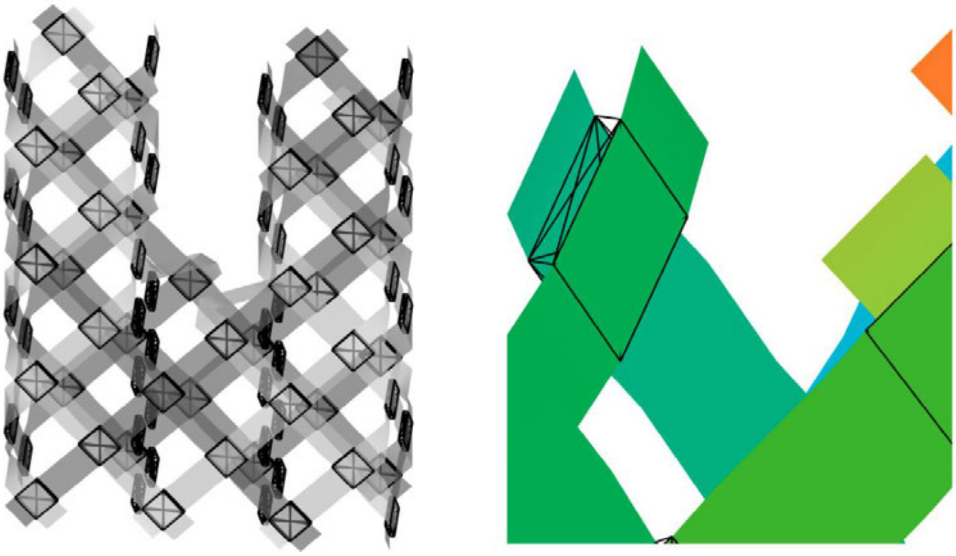


Figure 47: Strips are related to neighbors at strip-strip intersection by spring connections (visualized here by black-lined boxes) in the nonlinear relaxation process.

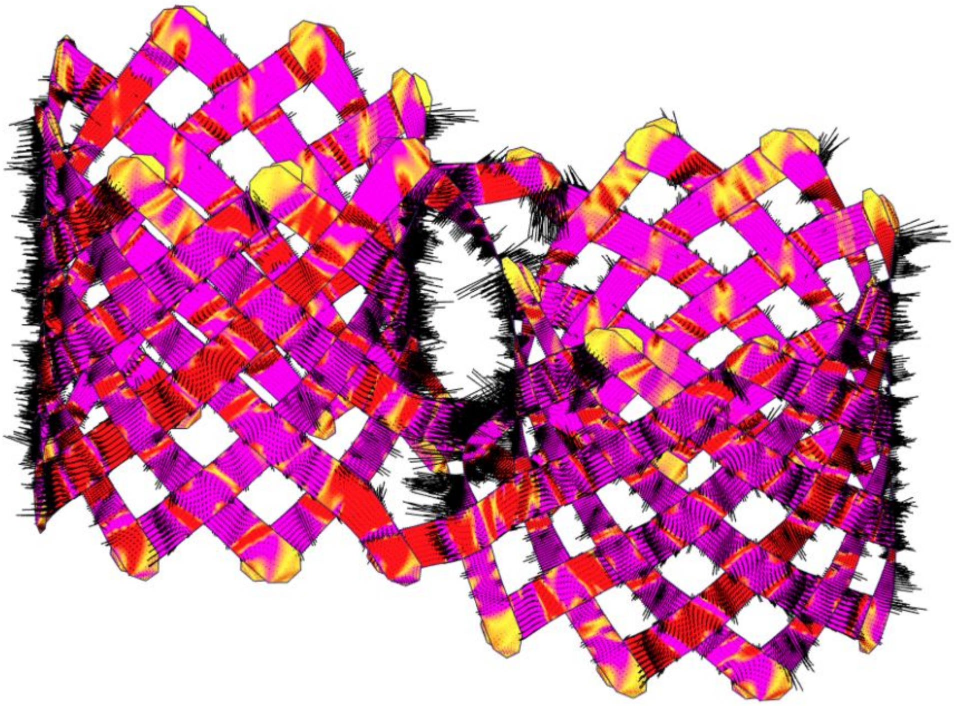


Figure 48: A heatmap visualization overview of all interacting forces in the strip-strip nonlinear relaxation process.

Figure 49: Evaluation of the method by visual comparison to physical prototypes.

Evaluation We evaluate the performance and generalizability of the method against geometric similarity and simulation performance. To assess simulation performance, we compare approaches to collision detection within the braid relaxation phase of the method to extrapolate the limits on complexity of currently achievable models. To assess geometric similarity we compare geometries of simulated results against physical examples. Simulation performance is a limiting factor to the complexity that can be represented, with the relaxation phase being the most computationally demanding due to monitoring line-to-line collision detection in the mesh (see Fig. 47). We tested several methods to evaluate collision detection performance. Using an input mesh with 11105 edges we obtained the following results:

- using a Spatial-Grid method (see Fig 47) [132] without multi-threading results in a running speed of 60 - 100 ms per frame;
- using an R-Tree search method results in 80 - 200 ms per frame;
- using a conventional line-to-line constraint when calculating collision be-tween all possible pairs runs at 6.1 - 7.5 sec per frame and runs out of memory for larger models.

The geometric similarity of relaxed braid meshes is visually assessed. In Fig. 49, two features are physically prototyped, and then modeled for comparison. In both cases, the macro geometry of the model conforms closely to the physical prototype, whilst yarn-to-yarn relations show some geometric deviation. The modeled braid appears looser around regions of large geometric transition (Fig. 49, right).

Figure 50: Strip-strip interaction for testing physical properties of braid (tension).

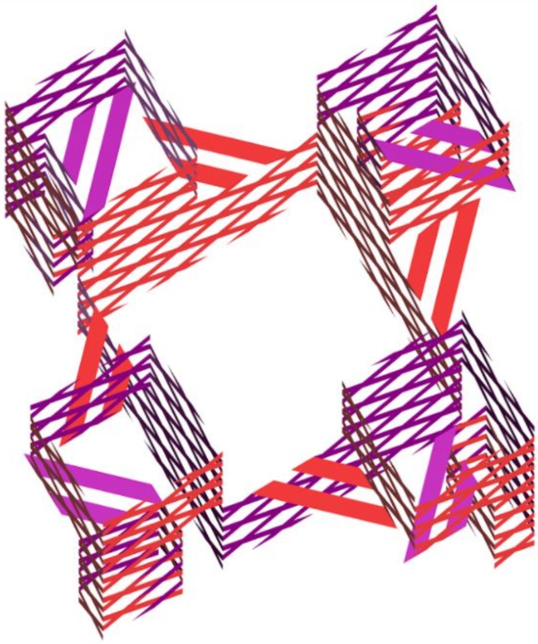


Figure 51: Before simulated relaxation, tile result of a braid displaying inversions of the braid surface. One global side of filaments is shown orange, and the other shown purple, to help visualize this condition of inversion.

2.3.4. Structural analysis by Finite Element Analysis (FEA)

Explicit and dynamic formulations of structural elements are particularly attractive for the simulation of large deformations and nonlinear phenomena. Especially in the context of form-finding, new and alternative approaches have recently emerged which are well-suited for these types of problems. The results shown in this paper clearly demonstrate the capacity and versatility of such formulations. Modern nonlinear Finite Element packages, the de-facto standard in engineering simulation, are completely equipped to perform simulations of complex mechanical systems and accurately describe their behavior, but it still requires a certain effort to organize entire simulation routines for large design explorations in Finite Elements environments. For this reason, analysis and evaluation of mechanical performance of braided systems could be divided into the following two steps:

1. Strip-strip interaction (form-finding and system generation, as developed so far);

2. Shell-like behavior (subsequent Finite Element Analysis for evaluation of system stiffness and buckling behavior, through further developments).

As in most cases, pre-stressing effects emerging from the deformation of thin and slender elements can be safely disregarded. The geometry emerging from the form-finding step of this paper could therefore represent the direct input for FEM analysis. This two-step workflow aims to explore and analyze the characteristics of mechanical performance, focusing in particular on the assessment of axial, bending and torsional stiffness, along with potential buckling behavior of the braided systems. These understandings from FEA would in particular help with predictions of long-term structural performance in the context of geometrical inversion of the braid surface (see Fig. 51 and Sec. 2.2.2), and self-weight exacerbated by material settling over time (see Fig. 52 and discussion of material settling in D3.1).

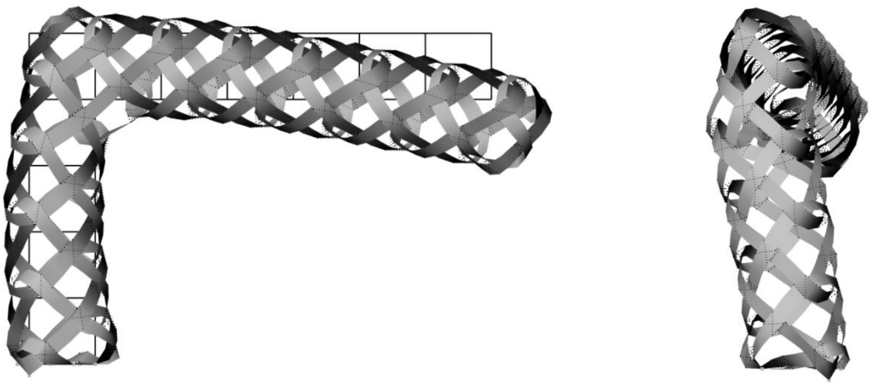


Figure 52: Self-weight, as simulated by the currently developed physics-based relaxation method described above. The addition of FEA or of a data-driven model could calibrate this simulation to the physical braids.

2.4 Relationship to WP1, regarding autonomous fabrication of braids

Though hand braiding is utilized for the development of mechanical understanding of braids (see above) and for the production of architectural vision (see Sec. 3.1), braided scaffolds in the project are meant to be autonomously fabricated by braiding machine (see D1.3). We therefore discuss both the constraints and the opportunities brought by the braiding machine, in terms of mechanical properties of the braids produced.

2.4.1. Braids made by the braiding machine

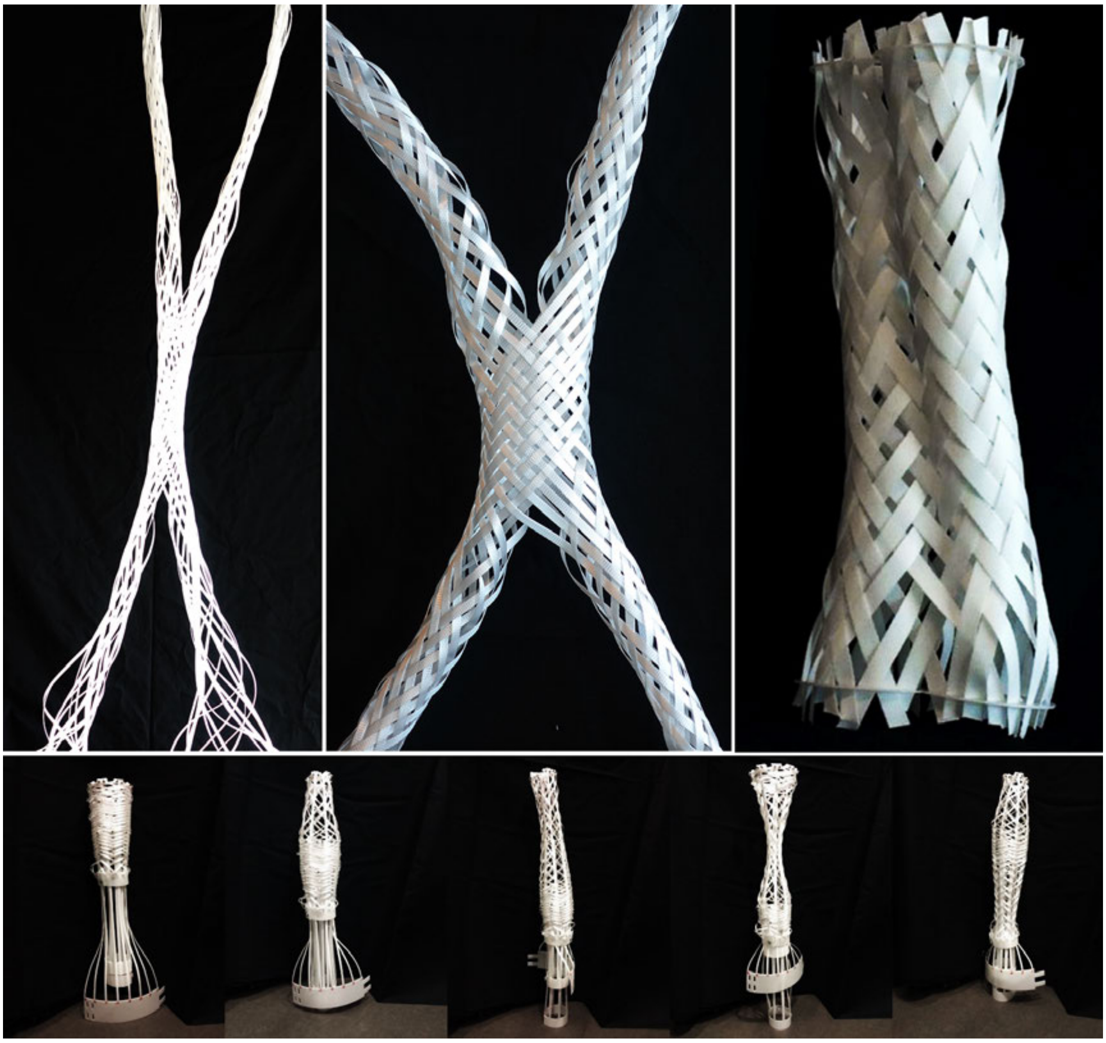


Figure 53: Examples of braids autonomously fabricated with the braiding machine (see D1.3).

The braiding machine brings several constraints that are not present in hand-braiding, particularly the constraint of all filaments having coplanar start positions and coplanar end positions. This means that a key braid type produced by the machine is a bifurcating 2D biaxial tubular braid (see Fig. 53, upper left and upper center). Due to the layout configurations of the braid machine modules (see D1.2, D1.3), bifurcating tubular braids made by the machine tend to have an oblong cross-section in the merged areas (see Fig. 53, upper center), unlike the rounder cross-section typically produced in these areas when braided by hand (see braids in Sec. 2.2). This oblong cross-section offers some advantageous opportunities when scaling up to architectural-sized artifacts (see Sec. 3.3.2). The braiding machine has also resulted in unique insights into braid mechanics, by resulting in the development of braid types that were not yet made through hand braiding explorations. Two important new braid types from machining explorations are:

- 3D braid made by switching some (but not all) filaments in neighboring 2D tubular braids out of their home 2D surface and into the neighboring one, resulting in a 3D braid that gives the geometrical impression of two 'fused' tubes (see Fig. 53, upper right);
- Triaxial braid in which the biaxial filament direction groups can be actuated separately from the third, vertical group, via separate anchoring at the filaments' ends (see Fig. 53, bottom row).

2.4.2. WP3 stiffening strategies

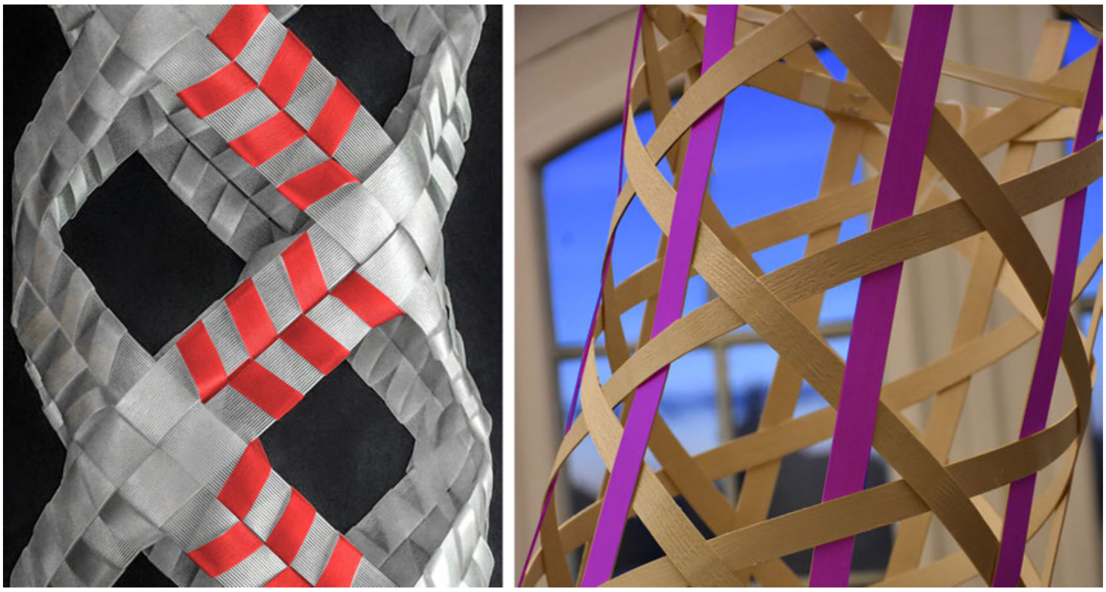


Figure 54: Two strategies for the stiffening of biaxial braid by adding a third group of filaments. (Left) Braid-weave hybrid, with added weave filaments highlighted in red; (right) triaxial braid, with added triaxial filaments highlighted in purple.

Here we briefly discuss the possibility of machining and automating some types of braid features described within this document. Though many of the investigated features of braid are primarily useful in the development of architectural vision (see Sec. 3.1), the strategies for structural stiffening and for increasing the size of the space between neighboring filaments are crucial to any practical implementation of building architecturally-sized (i.e., more than 2 meters in height) *flora robotica* bio-hybrids. The large sizes of gaps between filaments are a scaffold specification required to maintain plant health within the system (see Sec. 4.2.2), while the structural stiffness is a specification required not only to support the self-weight of larger scaffolds, but to support the live loads that would be continuously increasing in any growing system where the scaffold continues to serve the primary structural role, including the support of plants (and their resources), robotic elements, environmental loading (wind, rain, etc) and any loading occurring during occupation (sitting, leaning, and—eventually—second-story occupation). We can assume a significant amount of live loading during the period of the growth career when the braided scaffold is the primary structural support, as literature evidences (see Sec. 4.1.1) that plant elements will not be mature enough to be the primary support of single-story loads for 5 to 10 years, nor multi-story loads for at least that long, if not decades.

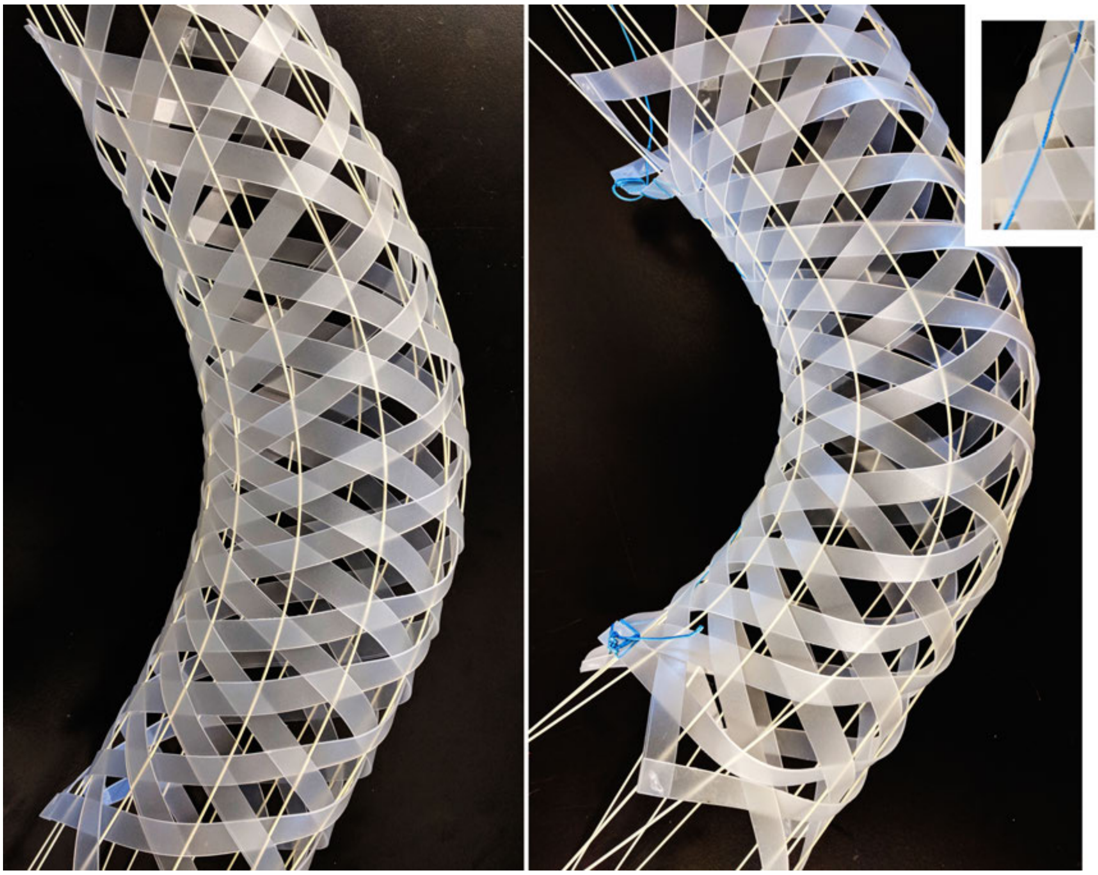


Figure 55: A PVC biaxial braid stiffened by the addition of GFRP rod triaxial filaments. (Left) The braid in its resting position after being mechanically actuated; (right) the braid in the position it holds when actively under the force of that same mechanical actuation; (upper right) a close-up of the actuation string, blue.

Therefore, we consider which stiffening strategies might be both the most effective structurally and the most implementable by the braiding machine. The most versatile of the stiffening strategies in terms of producible surface topologies, based on our material investigations throughout Sec. 2.2, is triaxial braiding with a sufficiently stiff material. This could be implemented either with all filaments being substantially stiff (e.g., all wood veneer, as in Fig. 54, right), or with filaments in the two biaxial directions being less stiff and filaments in the third vertical direction being substantially more stiff (e.g., GFRP rods in the triaxial direction, as in Fig. 55). In the first option of these, the material cannot be overly stiff, because it still needs to be manipulated by the force available from the braiding machine. In the second option however, the vertical triaxial filaments (see filaments marked in purple, Fig. 54, right) can be as stiff as structurally desired, without limit, because they do not need to be bent by the braiding machine. This is a significant advantage over other stiffening strategies using an additional set of filaments (e.g., Fig. 54, left), which require the new filaments to be manipulated in even more sophisticated ways than those in a biaxial braid (see filaments marked in red, Fig. 54, left). Extremely stiff triaxial filaments, not only do not need to be bent during braiding, but in principle to do even need to be moved. Indeed, the ends of the trixial filaments could be mounted in a static 'root' location, serving as the foundation of an architectural braid (see more discussion of this, and examples of simulated artifacts in Sec. 3.3.2).

Another important investigation in WP1 is not only the distributed fabrication of braid, but the distributed *actuation* of braid. Here we discuss the impacts that extremely stiff trixial filaments will have on the potential actuation of the braid. As is demonstrated in some of the braid examples already produced by the braid machine (see Fig. 53, bottom row), it is feasible and productive for the biaxial filaments (which in this case are much less stiff) to be actuated separately from the stiff triaxial filaments. This strategy in principle can be applied to any of the actuated biaxial tubular braids discussed in D1.3 (such as the 3 DOF braided manipulator). having much stiffer triaxial filaments than biaxial filaments may also present an added opportunity for possible actuation. In the tubular braid test where the biaxial filaments are flat PVC and the triaxial are GFRP rods, the braid is able to hold a curved shape in a resting position after being mechanically stressed, rather than needed continual mechanical stress to remain in a curved position (see Fig. 55, left). The braid does not however hold the tightest curve possible in a resting position, as can be seen by comparing the resting curvature (Fig. 55, left) with the curvature under active mechanical stress applied by an actuation string (Fig. 55, right). Though this braid type will hold its curvature after mechanical stress, the shaping is still entirely reversible, by applying an opposing mechanical stress via other actuation strings.

3 Growing Spaces

3.1 Architectural Envisioning of the Growth Career

Architectural envisioning develops speculative drawings and images of spaces that could be grown using the *flora robotica* system. These speculative visions are crucial for the overall development of the project, as they produce important feedback for the development of various project components. This is palpable in the transition from stut-and-node construction logics to braided construction logics, as well as in the development of investigations into braided structures. This feedback also helps refine the project components and their integration of roles, such that they can come together to form a cohesive architectural whole that is both useful and compelling for human occupants. Furthermore, while it is common for architectural envisioning to serve as a design tool when developing architectural prototypes and demonstrators for dissemination to the general public—such as in the future Social Garden—it is of increased importance in *flora robotica*, where the combination of long plant growth periods and a (relatively) short project timeline constrain the size and scope of artifacts that can be physically grown. In this context, envisioning and projections are the best available tools to extend our evaluations beyond the *flora robotica* artifacts able to be produced in a few years, to the artifacts, spaces, and use-cases that the system could in principle support.

3.1.1. Chronological development of holistic architectural vision

The desired characteristics for *flora robotica* have been previously defined in D1.1. In summary, these are: 1) targeting energy neutrality; 2) adaptability; 3) biodegradability; 4) self-repair; and 5) controllability. These are not directly spatial in character, therefore it is necessary to invent a suitable architectural 'vocabulary' that can compliment and integrate these stated objectives. This process of invention is conducted through 'envisioning'. Architectural envisioning can be understood as a mode of hypothesis making, with particular focus on spatial, construction and material attributes. Through envisioning, we develop hypothetical statements in the form of drawings, 3D models (physical and/or digital) and physical prototypes. Through the process of making these statements we speculate about elements that comprise the proposition (e.g., boundaries, components, occupants, etc.), attributes of those elements (e.g., size, material, function, etc.) and relationships between elements (e.g., relative scale, spatial arrangement, role, etc.). Completed statements, or propositions, can then be 'tested' by interrogating their plausibility, feasibility, novelty or solutions to the stated objectives, or sub-objectives under consideration. Through an iterative process of architectural hypothesis making and testing, we are able to gain greater clarity and nuance in how to achieve the desired characteristics of *flora robotica* through architectural means.

From an architectural perspective, our envisioning process takes point of departure in the assumption that **Architecture** serves two overall objectives: 1) to offer some form of advantage; 2) to offer inspiration [74]. However, *flora robotica* represents a radical departure from conventional architectural outcomes. In this case, many of the normative advantages that can be used as measures of success for an architectural proposition, do not apply and therefore cannot be leveraged to guide its design. We therefore utilize the five characteristics stated above as principle desired advantages and develop spatial propositions through which to give these advantages material presence. In addition, our envisioning speculates upon a diverse range of further questions including issues of boundary and context, developmental plasticity and embodied memory. To guide our approach to meeting the objective of offering inspiration, we attempt to envision novel and unique architectural environments defined through the unexpected partnership of natural plants. We attempt to envision new functionalities not conventionally associated with architecture, such as long-term morphological adaptation, self-renewal and repair, and new forms of interaction between human occupants and biohybrid environments. The initial envisioning con-

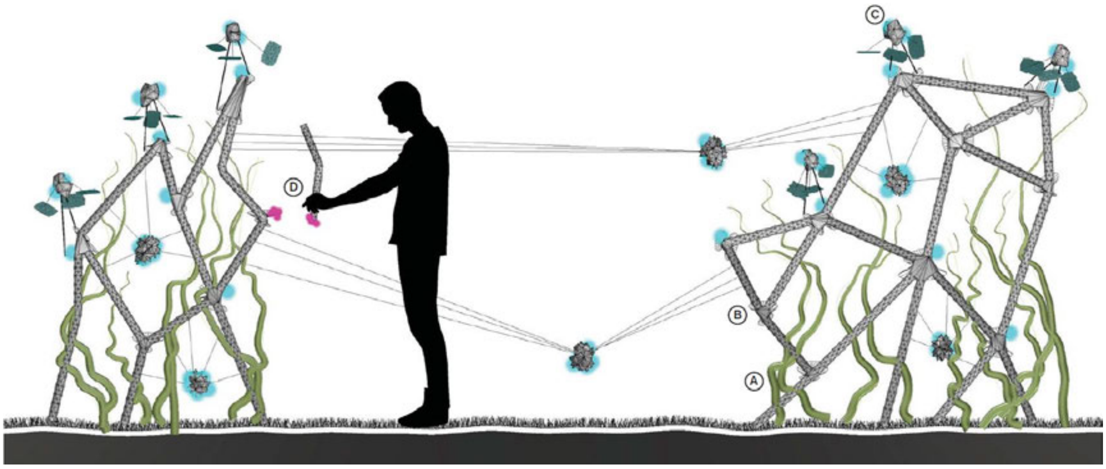


Figure 56: Drawing FR-GC-1-01: LocoKit Modular Concept. Containing constituents of (a) plants, (b) modular robotic scaffold based on LocoKit, (c) robotic nodes as movable and data transferring 'electronic fruits', (d) bio-hybrid request for modular extension.

cept is based on the use of the LocoKit[1], a conventional robot construction kit comprising rods and nodes allowing a user to build modular structures with embedded sensing and actuation functionalities. Fig. 56 illustrates two structures located within distinct regions of plant growth. Plants are shown growing around and upon these technical elements. This introduces a core concept of 'scaffolding' that remains central throughout the architectural vision development. The idea of scaffolds for plants to grow and be guided upon has a clear horticultural heritage, and remains a common practice. In the case of *flora robotica*, we appropriate this concept and advance it by considering the scaffold as an adaptable, modular robotic structure. However, LocoKit has proven overly restrictive in its modular and mechanical characteristics, which reduce potentials for nuanced interaction with plants. To address these concerns, we have moved to the use of braided structures to fulfill the role of the adaptive scaffold. The rationale for moving to braid has been described in D1.2, but in summary braid offers: a rich space of possible topologies; a construction logic that enables the production of structures with tailored and local kinetic behaviors; braids can be made from a diverse range of materials and materials can be combined locally to grade a broad variety of attributes (mechanical, optical, aesthetic, etc.); integration of sensing and actuation can be considered in a variety of ways, from nodes that are independently attached to the braid being a mixed computational substrate itself. In concert, these attributes represent a much greater potential for promoting interaction between the technical and biological components of *flora robotica*. Fig. 57 revises our initial concept diagram. Technical elements are shown to be more directly integrated and in 'developmental plasticity' with plant growth—responding to growth, but also steering it to produce specific spatial conditions for occupancy. Human interaction is maintained, and braided elements are able to support plant growth in a manner of ways: allowing growth within; growth upon; wrapping to support growth. Braid can also be produced with distinct topological and morphological characteristics, as seen in Fig. 58,

[1] http://locokit.sdu.dk/

demonstrating the idea of an integrated and sensitive local tailoring to achieve system and design goals. In addition, the concept of modularity can be reconsidered in a more nuanced way as an embedded property of braid construction logic. The use of braid like lattices for creating stiff,

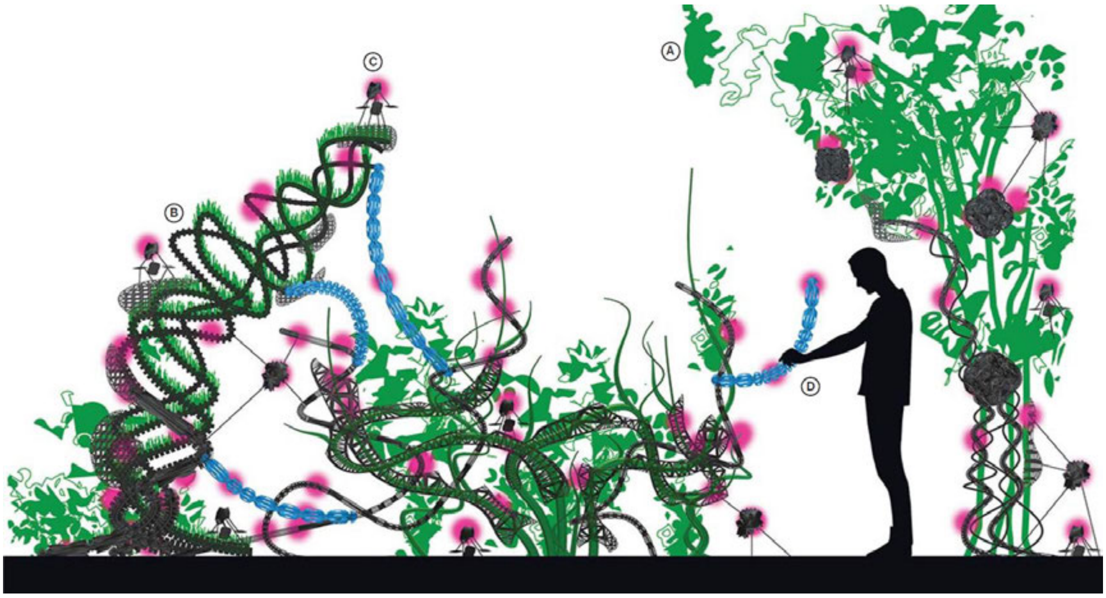


Figure 57: Drawing FR-GC-2-01: Braided Scaffolds Concept. Containing constituents of (a) plants, (b) braided scaffolds, (c) robotic nodes as movable and data transferring 'electronic fruits, (d) hand-braiding extensions to the biohybrid.

structurally performing structures has been demonstrated at architectural scale [11]. Although not strictly braids (as there is no interlacing at material intersections) these structures provide evidence that braid-like patterns at larger scale posses potent and inspiring aesthetic qualities. Achieving material interlacing at architectural scale presents design and construction challenges, especially when considered through conventional approaches to materials, material sizing, tectonics and performance. In the cited work timber lamellas are specified at a thickness that provides adequate bending performance across the length of the member, but inadequate bending performance to allow interlacing. In this case, the inability to connect through interlacing presents material fixing and logistical construction challenges in comparison to actual braiding technique where self-structuring properties emerge through early construction, allowing the braiding process to be arrested without adverse impact to performance. In the context of *flora robotica*, the ability to arrest and resume construction at will can be leveraged as a mechanism of artificial adaptation. In Fig. 59 we explore the idea that an architectural scale braided structure might be composed of smaller scale braided filaments - a braid of braids. Such a scalar nesting strategy could enable the necessary interlacing at material intersections (providing compliant structural performance) and to support the idea of 'continuous' construction (adapting to changing circumstances such as plant growth, or modified architectural objectives). Fig. 60 explores a detail of spatial characteristics resulting from this approach, with a portion of constructed triaxial braid emerging from individual braided filaments below. A similar architectural assemblage is envisioned as a mature urban garden in Fig. 63.

In *flora robotica*, braided scaffolds serve a number of functions at different scales. Where the previous three figures examine their role in the organization of space at a macroscopic scale,

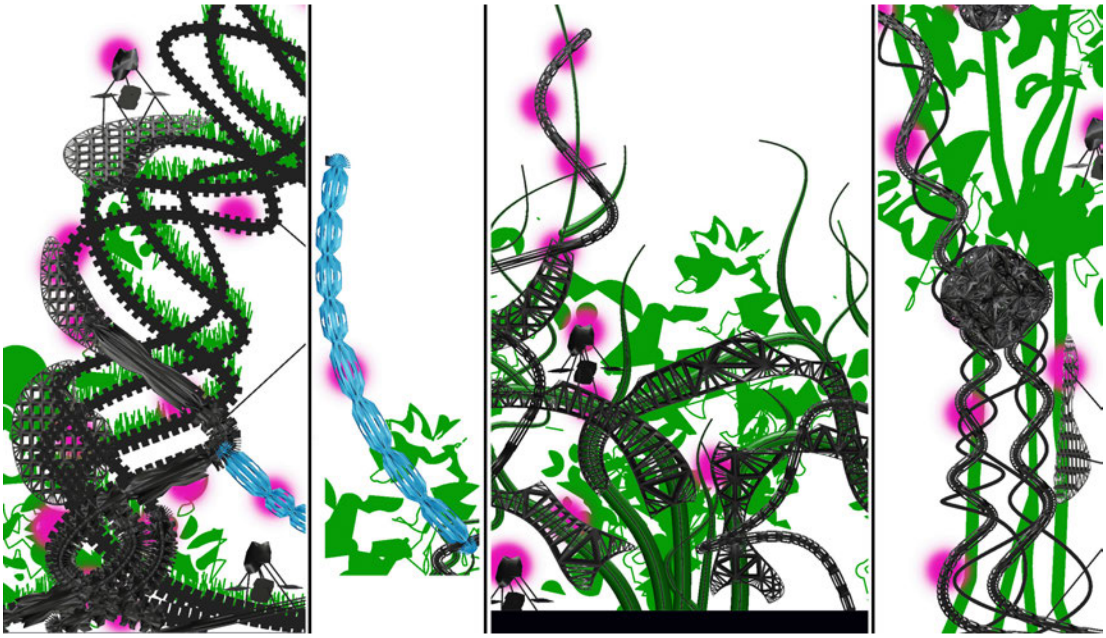


Figure 58: Detail of Drawing FR-GC-2-01: Braided Scaffolds Concept showing diversity of braid topologies, morphologies and supporting a variety of interactions with plants.

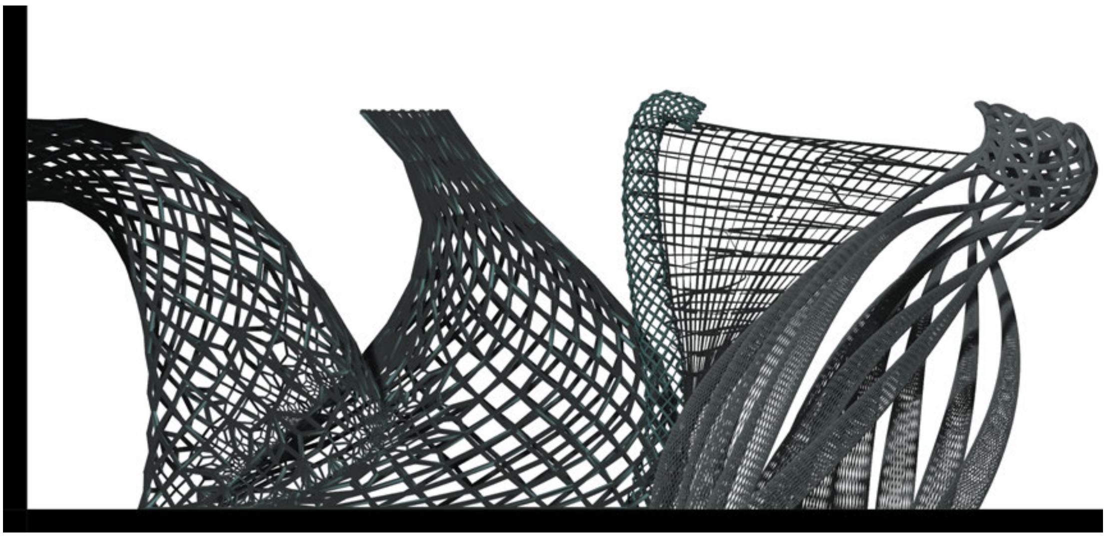


Figure 59: Envisioning braids at architectural scale.

in Fig. 62 we examine how robotic nodes for steering plant growth can be incorporated with a braid structure. Attention is paid to relative scale between node, material width, braid angle, unit cell size and configurations of node populations (right). The study on the left explores an additional role for the nodes as junctioning elements that enable the braid to extend its topology beyond surface geometries and into fully three dimensional configurations. Figure 63 examines

Figure 60: Detail of Fig. 59 . The macro braid is composed of filaments which are themselves braids. The architectural assemblage is a braid of braids.

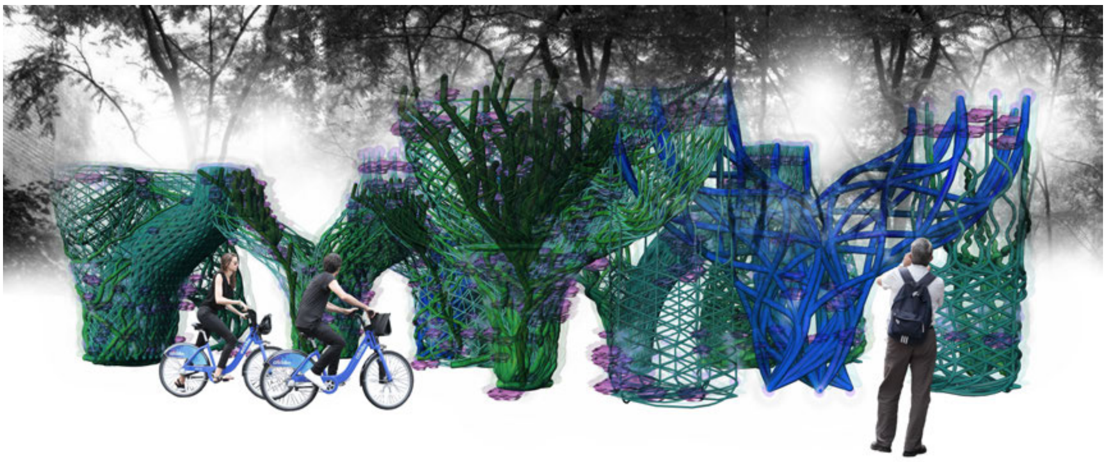


Figure 61: Visualisation of a hypothetical mature urban braid garden.

a complete *flora robotica* environment within an urban garden context. Here we envision the progressive development of the system, paying consideration to both spatial attributes, system functionalities and characteristics. Frame (A) provides a visualization of the mature state. Frame (B) defines the preliminary state where a site is 'seeded' with planted braids, structural braids and reservoir braids for collecting rainwater. It is suggested that braids actively steer plants that grow within, or around them. Steering occurs through either mechanical influence or resource allocation - in this case, collected water. Water distribution is also used as a live load for

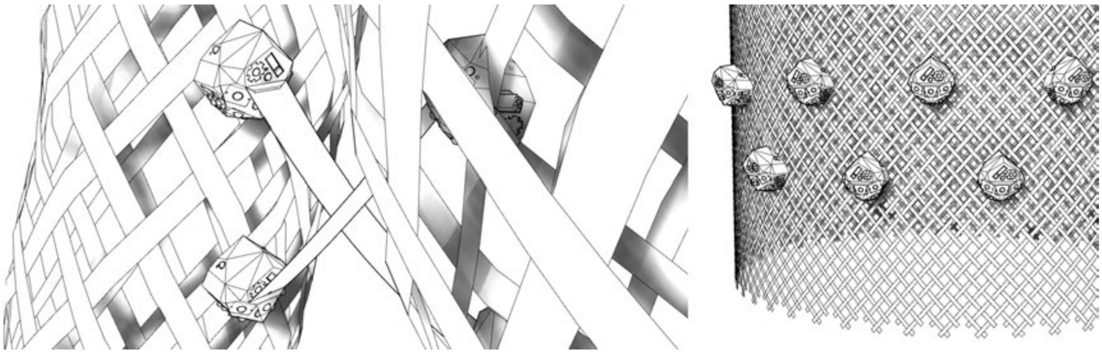


Figure 62: Exploring the relationship between robotic nodes and braids. Nodes are supported by braids (right) and braids are extendable into fully 3D configurations through nodes (left).

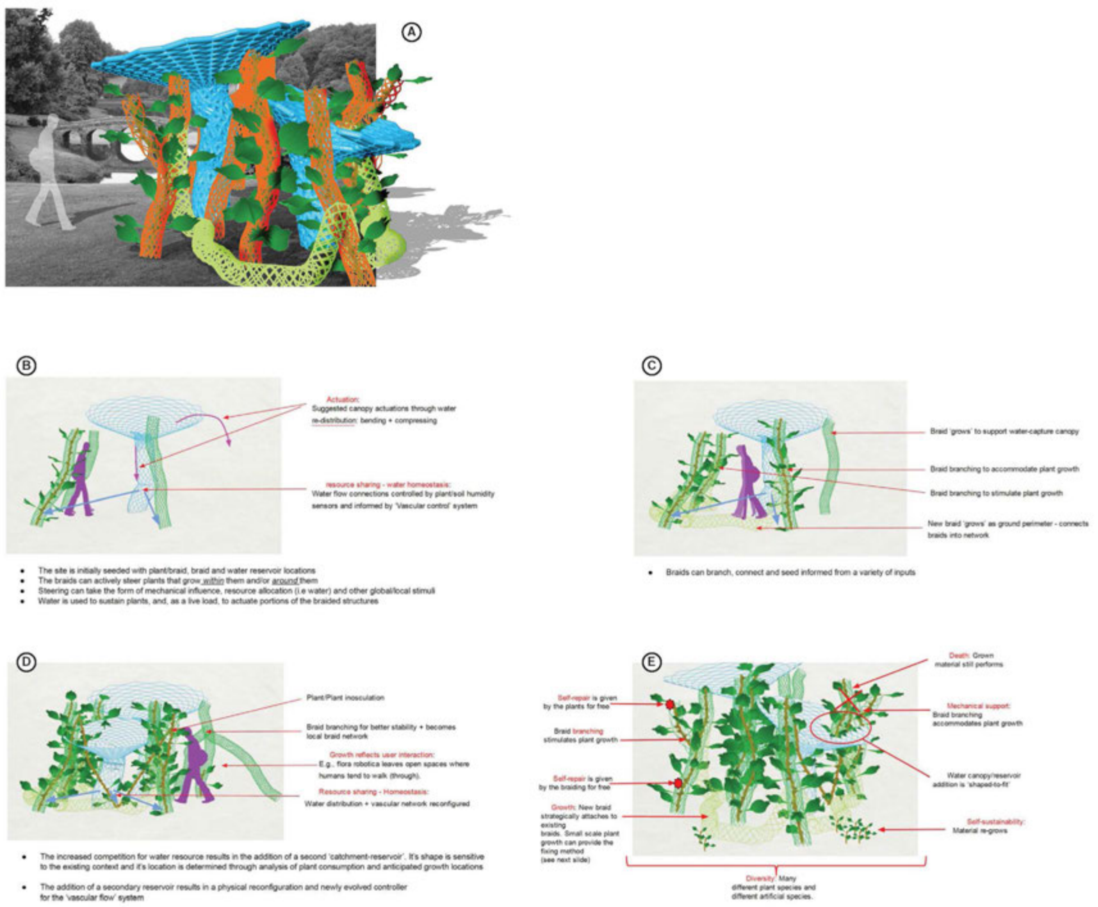


Figure 63: Envisioning a 'growth career' from initial 'seeding' to full maturity. Desired characteristics of *flora robotica* are indicated through the timeframes.

actuating braids. In frame (C) braids artificially grow to provide: 1) further support to the water-capture canopy; 2) branching routes to accommodate plant growth; 3) branching routes to stimulate plant growth and bifurcation; 4) perimeter connections to link braids into a network. In frame (D) plant to plant inosculation provides long-term structural capacity. Growth of the system reflects habitual patterns of occupancy, and increased competition in resource sharing has resulted in a second water-capture canopy being added. In the final frame (E), self-repair is shown occurring within plants and braids. Death of biological material is shown to still serve a purpose as it still possesses useful mechanical properties. The system has self-sustainability as self-seeded material grows and gets incorporated, and the system has rich diversity across plant and artificial species.

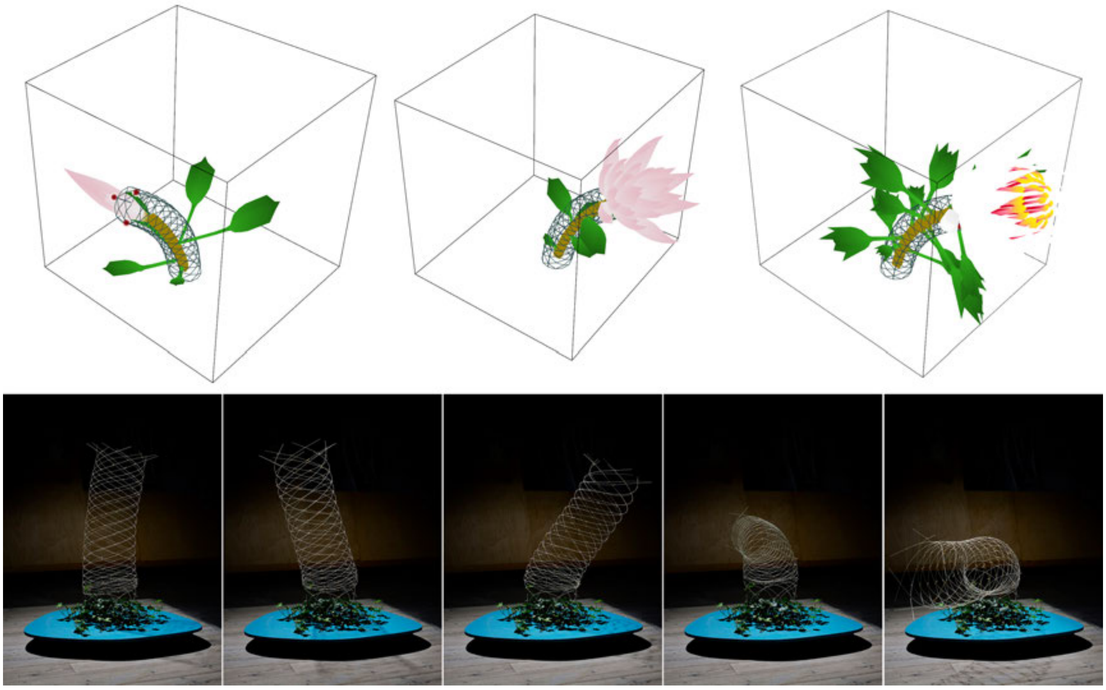


Figure 64: Actuated braids might be employed to actively steer plant growth and encourage specific mechanical characteristics (top). A physical actuated braid prototype demonstrating the range of possible movement (below).

The visualization portion of Fig. 64 (top) explores the idea of an actuated 3-DOF braid that can manipulate plant orientation. The premise for this concept is that a plant might gain advantage by growing within a braided, actuated, exoskeleton that can direct it towards preferable conditions not sensed by the plant. Being a part of a distributed and decentralized network, the braid benefits from collective information that exists beyond the perceptual scope of the plant. Another function of the braid could be to ‘exercise’ the plant and encourage long-term adaptation of mechanical properties, through controlled loading, in anticipation of future architectural use scenarios. In Fig. 64 (bottom) we show a physical actuated prototype of the concept. The control aspects for actuated 3-DOF braids is covered in D1.3.

In addition to actuated kinetic braids, we have speculated with the idea that other classes of braids might have much longer durations of adaptation that are more tuned to architectural and plant growth time scales. This class of braid could be robotically or manually ‘grown’ through

Figure 65: Individual braids can be assembled to construct familiar architectural conditions with unfamiliar attributes.

a continuous braiding process [48]. In Fig. 65 we show a small population of large-scale (ca. 2 m tall) hand-produced braids. Unbraided strips hang from where manual braiding has been arrested, offering the potential to resume and extend the braid whenever required. This population also demonstrates how a collection of individual braids can be used to create compelling spatial conditions of deep boundary, extended threshold or routes for both plant and human occupants. A number of spatial relationships between braids and plants can be envisaged, offering an extensive palette of functional and aesthetic conditions that can be selectively deployed to achieve architectural advantage. In Fig. 66 we examine (clockwise from top left): braid and plant in juxtaposition (artificial growth to support plant stimulated by natural plant growth); braids as objects in a landscape (placemaking and landscape navigation); plants growing within braids (offering progressive structural advantage through growth); plants colonizing conditions created within braids (developmental plasticity and embodied memory through exploitation of environmental niches).

In Fig. 67 we speculate on possible qualitative differences of plant growth upon a braid. In the upper section, we imagine steered growth at high resolution with plants growing along selected braid strips. In the lower section, we imagine steering a progressive dense vertical coverage. These two hypothetical strategies provide distinct visual qualities, but we can also infer distinct mechanical properties emerging from such close plant braid interaction.

Figure 66: Braids and plants can be arranged in a diverse set of relationships, each privileging specific forms of interaction.

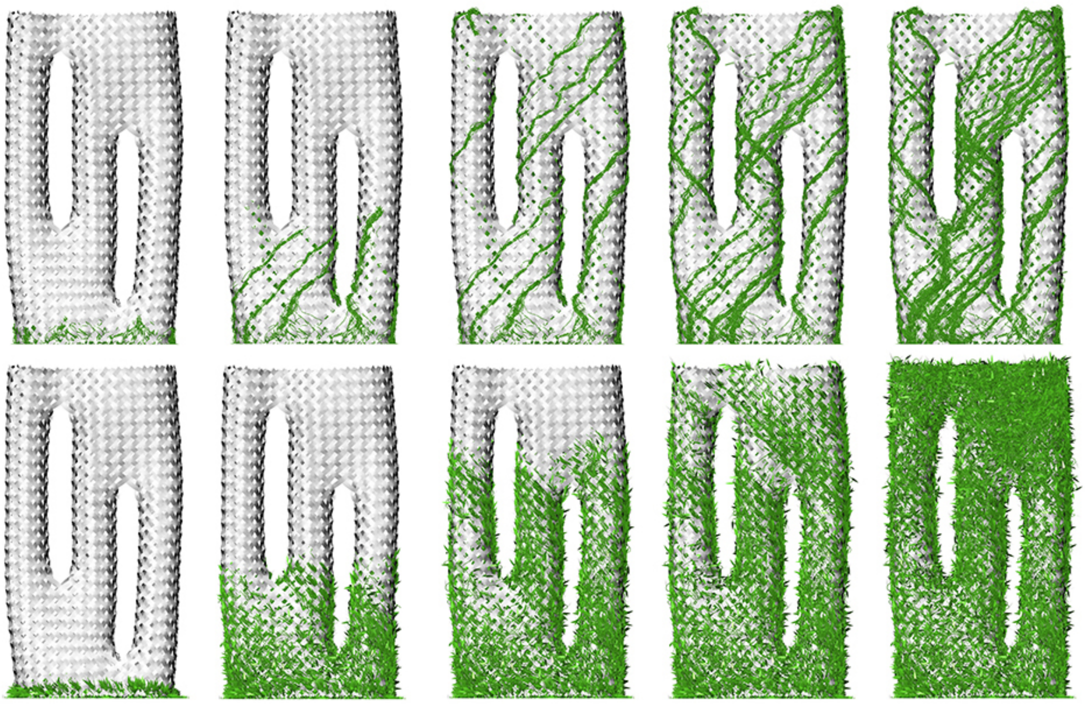


Figure 67: A visualization of two speculative strategies for steering plant growth over a braid. Plants are guided along discrete strips (top) or plants are progressively encouraged towards full coverage.

3.1.2. Use propositions at each scale

In this section we aim to bring together discrete elements in an effort to explore complete, or near-complete environments that integrate desired characteristics across scales, from material, to component, to environment. Fig. 68 shows an early stage mock-up exploring possible physical

Figure 68: An early stage mock-up exploring possible physical characteristics of a *flora robotica* site with a diversity of braids having distinct roles.

characteristics of a *flora robotica* site. Static braids are used to define a soft boundary into an 'interior' space. These braids are envisaged as long-term adaptive elements that can adjust the spatial boundary through further braiding—growing further vertically, or connecting to each other as a way of consolidating the perimeter. The interior space is occupied by an actuated braid which can lean towards arbitrary targets within its hemispherical field of operation.

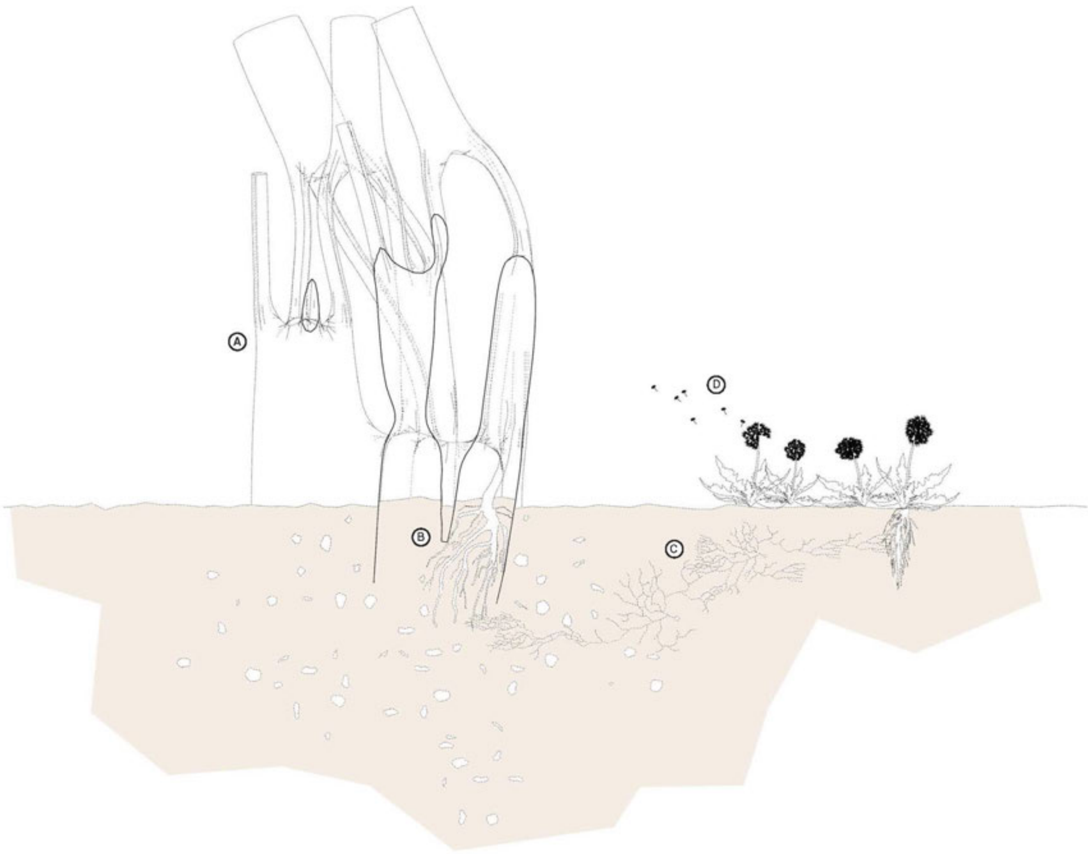


Figure 69: Drawing FR-IS-2-02. This is a Speculative study of *flora robotica* becoming an extended network through natural integration with a common mycorrhizal network (CMN)—the 'Wood Wide Web.

Fig. 69. Here, we present a speculative study of *flora robotica* becoming an extended network beyond its boundary through natural integration with a common mycorrhizal network (CMN). CMN's form the critical infrastructure for what has been termed the 'Wood Wide Web' [36]. In addition to potential CMN (fungal) connections, infiltration of floral species is alluded to through the air-borne achenes from mature Taraxacum. In this case, the braided scaffold (left) is shown anchored into the ground. Fig. 70 includes 'potting' as a further ground connection approach, with horticultural equivalents shown for reference. The 'potted' condition permits manual spatial relocation by human occupants, thereby providing another strategy for spatial adaptation. In figure 71 we speculate on the spatial characteristics of a mature flora robotica architecture in an external context. Braids are shown having grown together to create the boundaries of an

interior. The braid surfaces support robotic nodes that continue to steer plant growth towards functional and aesthetic objectives.

Figure 70: Drawing FR-IS-2-01. Study of braid connections to ground and comparison to their horticultural equivalents.

The following architectural use case scenario (Fig. 72) is envisioned as a 'growth career' through a series of transition states. Here, we explore how a predetermined architectural intention might adapt over time towards new architectural objectives. The starting state is defined by two separated 'cavity walls' that frame a short path between them. We employ the Kagome lattice [88], a particular case of tri-axial braid, to define the predetermined scaffold walls which support plant growth, robotic node arrays and 'active' braids that can artificially grow to supply key resources including power, water and artificial light. The plan portion of the figure (bottom) indicates a defined zone for the growth of a self-organized canopy. Active braids begin to reach across the divide and are quickly colonized by fast growing climber species (e.g., Lonicera or Fallopia). In this case, self-organization requires feedback of structural performance to develop the extending cantilever. We speculate that this adaptation to modified architectural objectives requires minimum introduced energy as the majority of accumulated material occurs through plant growth. We have explored certain aspects of this proposition through physical prototyping as seen in Figs. 73 and 74, focusing on construction and spatial characteristics rather than

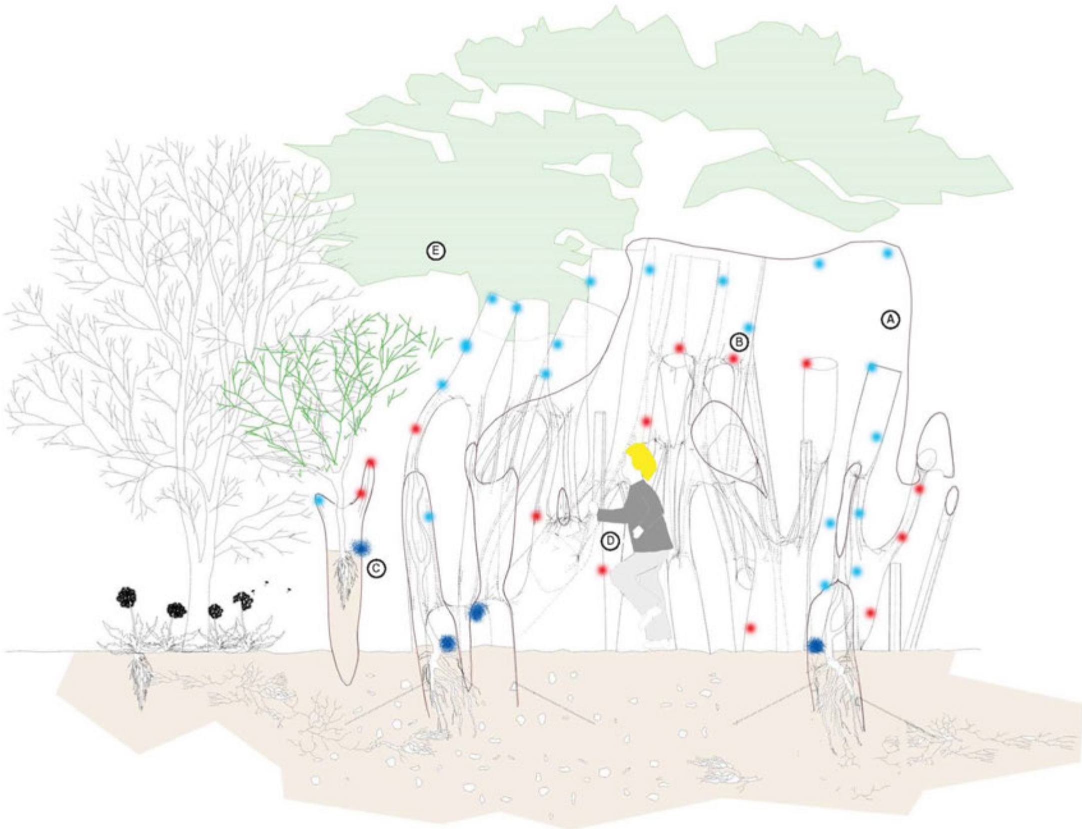


Figure 71: Drawing FR-IS-2-03. Notional section of a mature *flora robotica* architecture. Braids have coalesced to define a fully enclosed space capped with a mature Carpinus canopy. Outer edges of braid have become stiffened through internal plant growth, while internal braids remain pliable and reconfigurable.

implementation of technical infrastructures. In Fig. 73 it can be seen how the introduction of heptagonal singularities within the regular hexagonal mesh give rise to non-planar geometry. In this case, we develop a connecting cylindrical 'socket' between the two planar faces of the cavity wall which provides structural capacity. In Fig. 74 the configuration of the two walls establishes an extended threshold that invites human occupants to pass through into the space beyond. The right-hand wall gains stability through deformation of the plane rather introducing non-planar features through topological of the lattice. In this case, the artificially growing braid also acts as a support for the lattice. In the top left frame of Fig. 74 it can be noted that the lattice changes from a triaxial configuration (Kagome) to a standard bi-axial braid. This purposefully weakens the braid and creates larger cells through which strategically planted Elephant grass can grow as a living triaxial element. However, over the course of this exhibition, the interior environmental conditions were not conducive for long-term plant growth, so this proposition could not be demonstrated.

Further use case scenarios have also been explored in the context of a Master's of Architecture program, run by partner CITA. Students have been introduced to the *flora robotica* project through a series of workshops held between September 2017-Dec 2018, and invited to envision architectural use cases for braided scaffolds that incorporate living biological agents. In the following three cases, the visions have been developed in the context of urban farming scenarios. In Fig. 75 a complex braided geometry is developed for an interior condition. The aim is to negotiate between providing structural capacity and exploiting natural light from a nearby window to create a variety of growing conditions for a diverse collection of herbs. In Fig. 76 a large scale braid serves a dual role as scaffold for growing common vegetables, and climbing frame for children. In Fig. 77 students speculate on the use of dense surface planting across a braided scaffold to provide adequate shading and humid conditions for supporting the aeroponic growth of potatoes. Whilst these three use cases may be criticized in terms of plausibility, they nevertheless serve as evidence that the underlying premise of bio-hybrid architecture can inspire novel propositions with relevance to certain current societal needs.

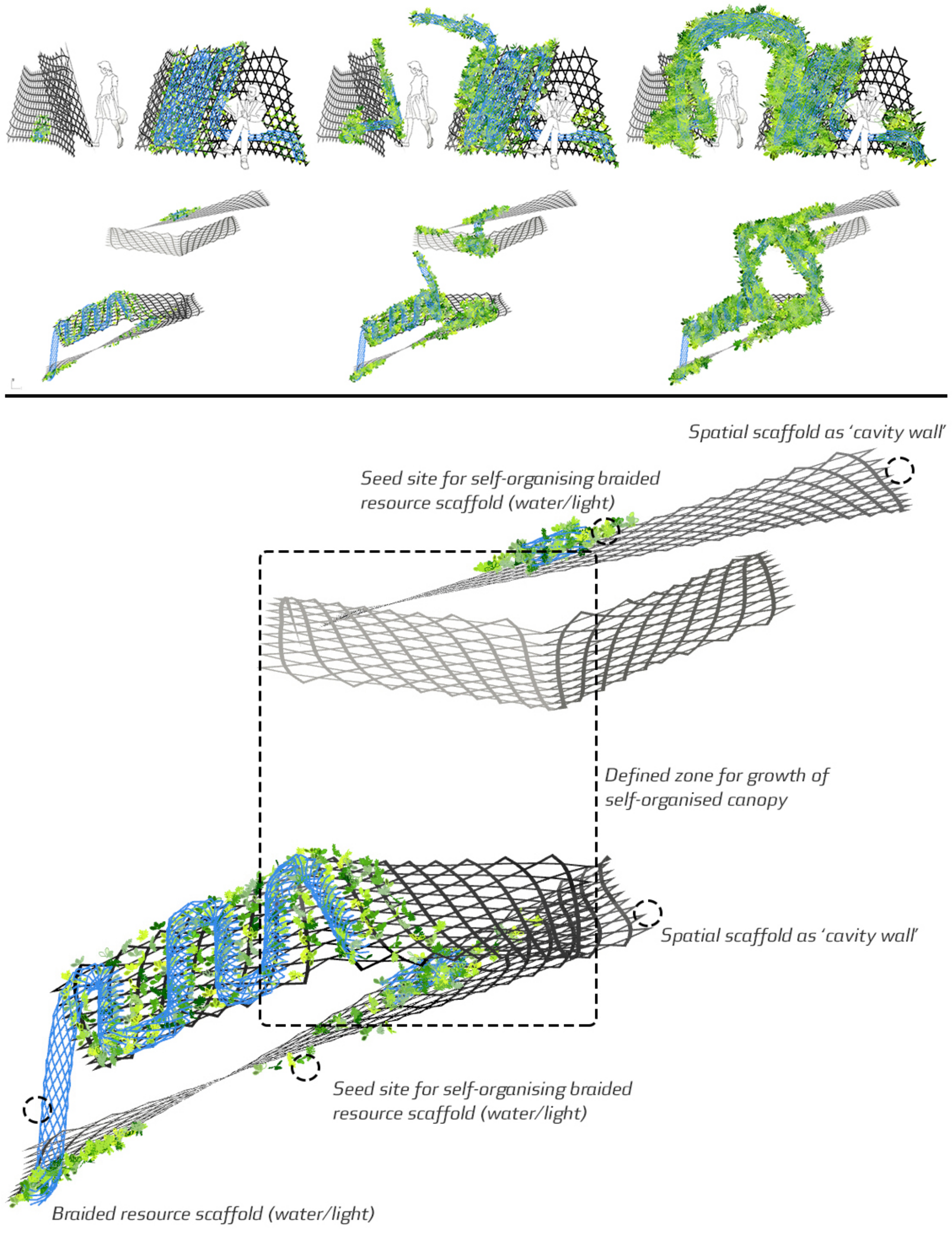


Figure 72: Envisioning another growth career with focus on combined steered artificial and natural growth towards new architectural objectives - in this case a canopy between two separated walls.

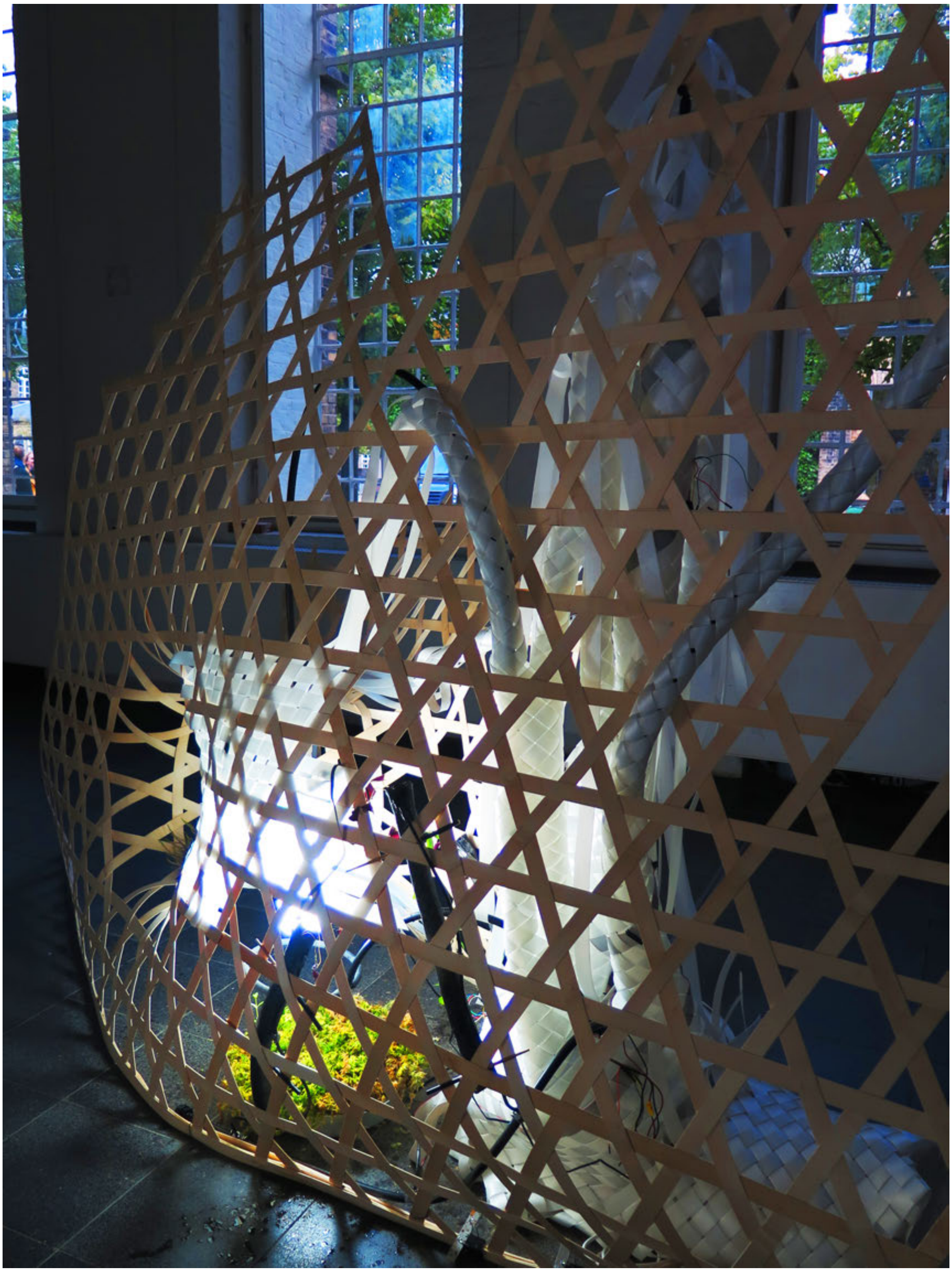


Figure 73: Detail of a Kagome lattice wall braided out of plane to provide structural stability.

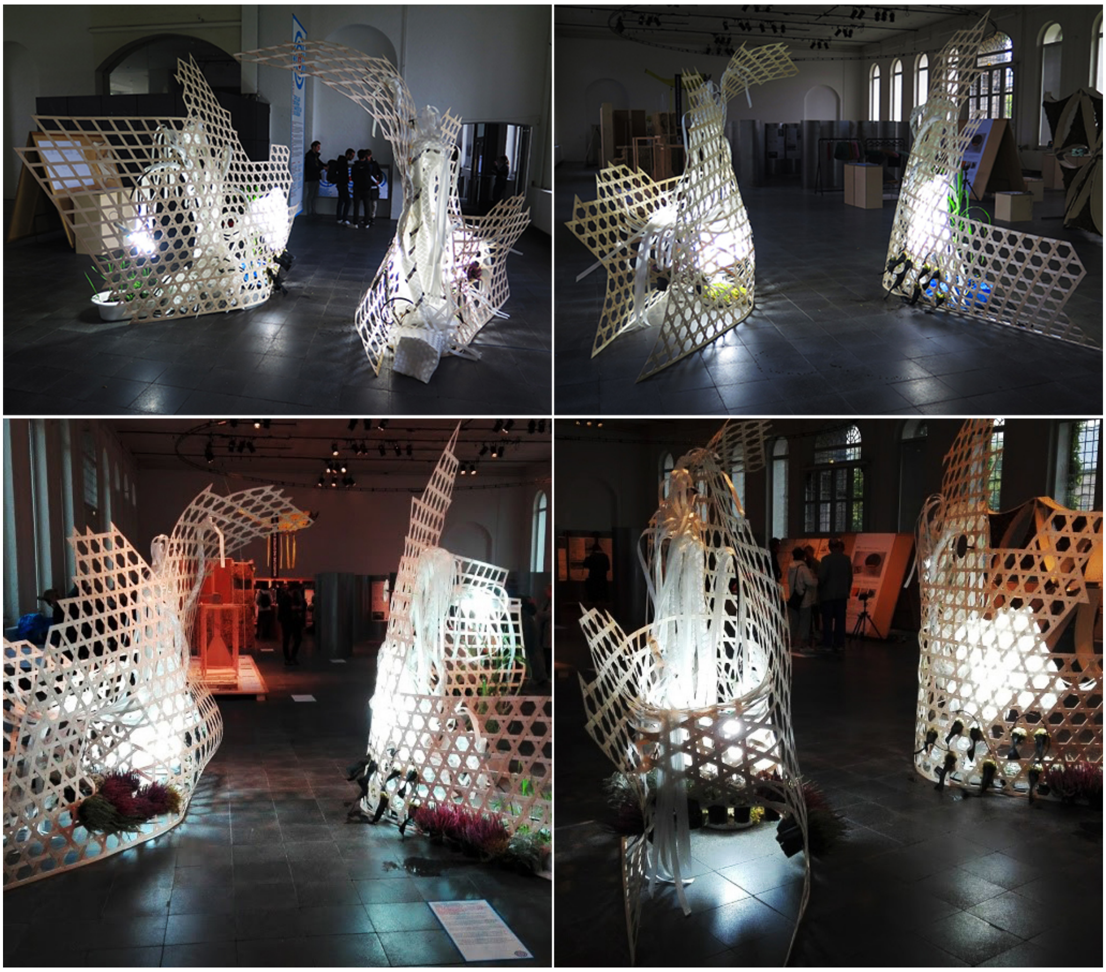


Figure 74: Views of the flora robotica exhibit within the 'Circular Economy' exhibition, KADK. The exhibit acted as an extended threshold entrance into the rest of the exhibition. Braids and plants fulfill a diverse range of roles, from structural, to adaptive, to experiential.

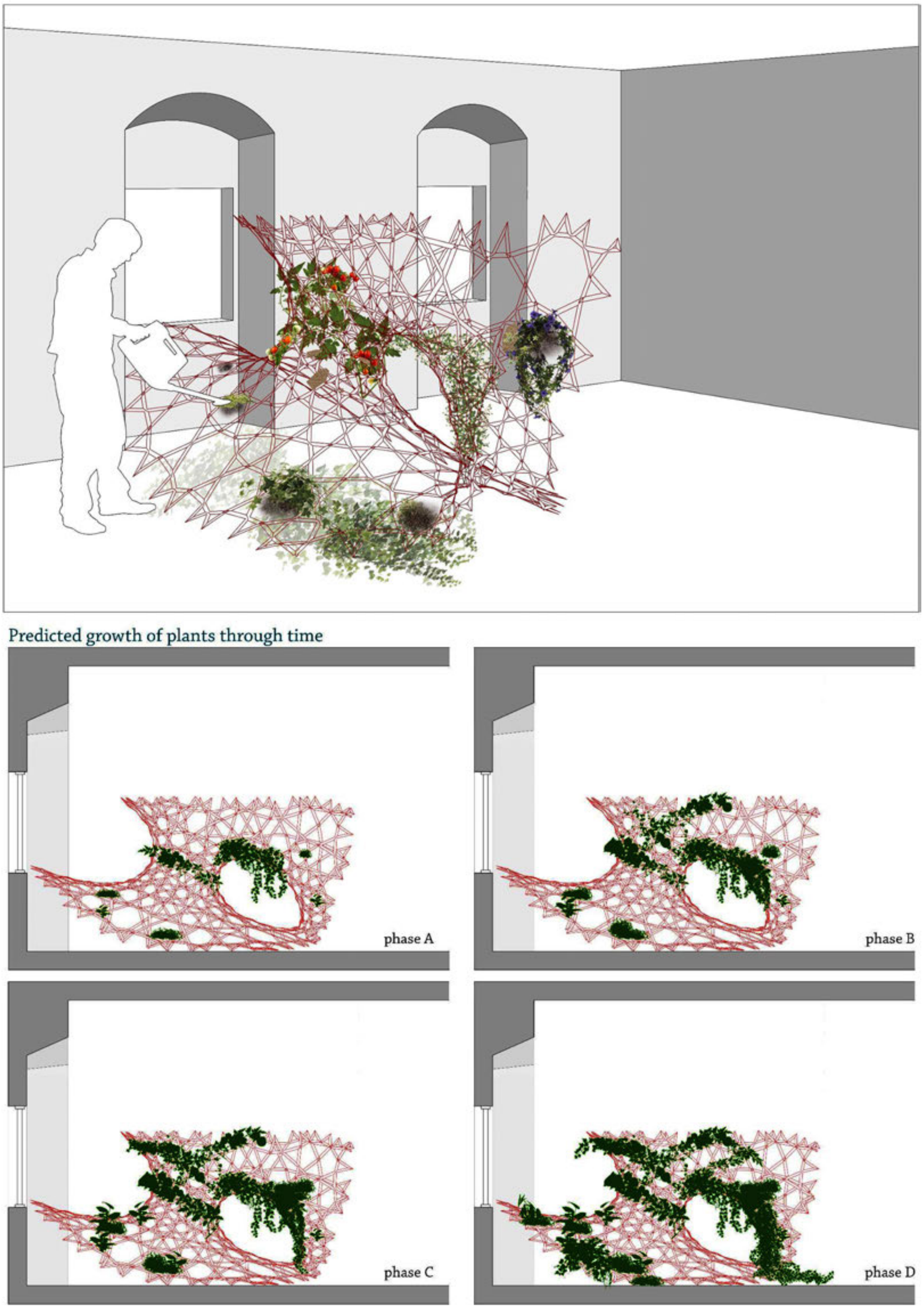


Figure 75: Visualization of possible use case scenario as interior urban farming, by Master's of Architecture students from KADK.

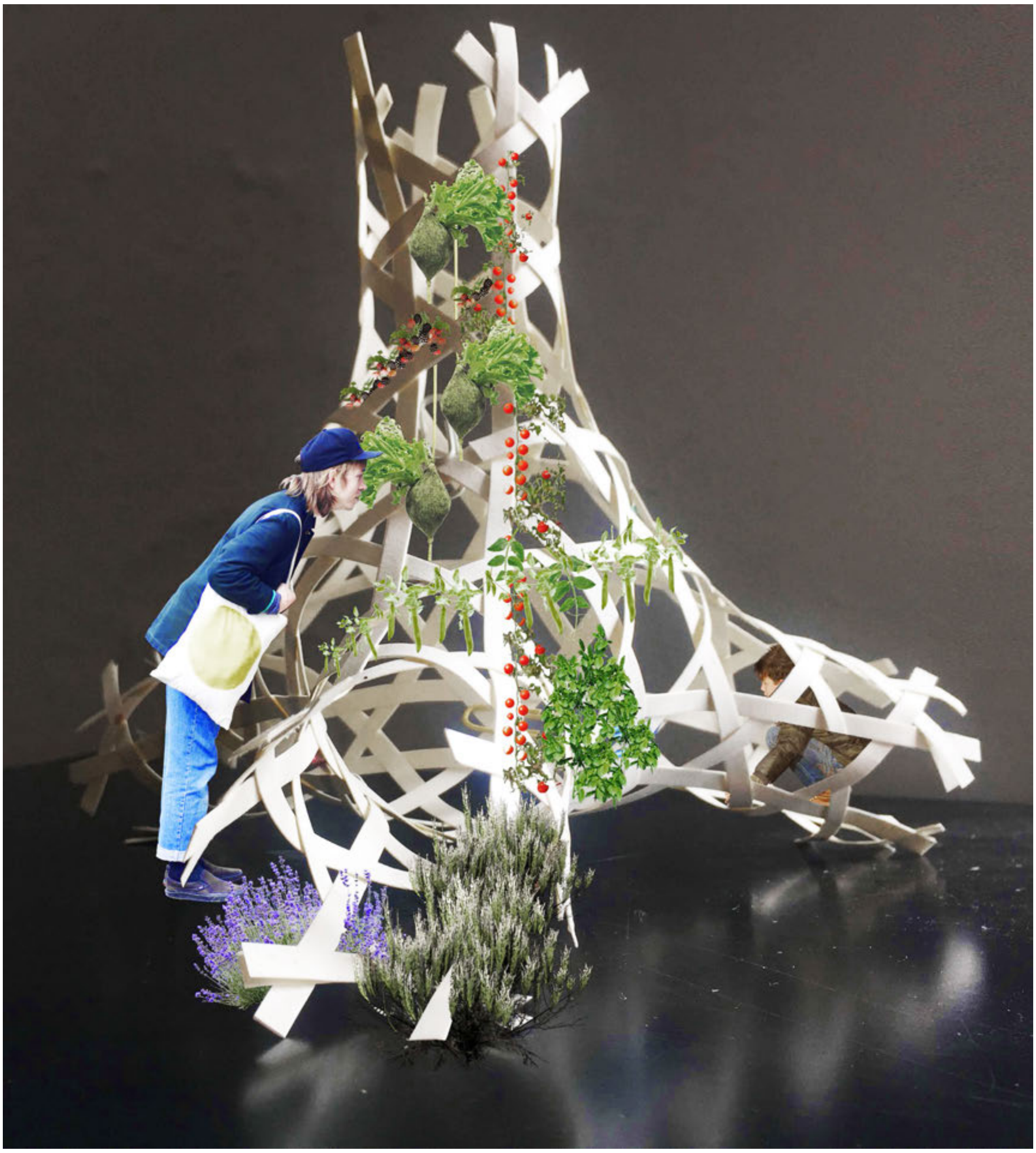


Figure 76: Visualization of possible use case scenario as exterior urban farming and children's climbing frame, by Master's of Architecture students from KADK.

Figure 77: Visualization of possible use case scenario creating interior environments suitable for interior urban farming through surface coverage of shading plants, by Master's of Architecture students from KADK.

3.2 Reviewing the systems and functions embedded in FR grown artefacts

3.2.1. Overview: fitting it all together

Growing living architecture in a bio-hybrid system based on natural plants and robots comes with a number of advantages compared to current housing construction techniques. The addition of material and the material itself is cheap, logistics are minor as the material grows at the site. Hence, energy expenditure for transport or production of building material is greatly lessened. The construction (growth) process is continuous, allowing the system to indefinitely compensate for wear or changed requirements, such as heavier loads on a bridge. The creation of pleasant and healthy environments for habitation is supported by natural components, such as trees and flowers, in lieu of concrete, bricks, or plaster [72]. Fighting air and noise pollution but also an increasing heat [143, 98] in our ever growing mega-cities is simplified once buildings by default consist of so-called 'green infrastructure' (e.g., green walls, green roofs, [117, 136] that possibly absorbs pollutants and noise. A living house can react to its inhabitants, was potentially evolved for resilience, and adapts to changed needs. Hence, living architecture based on plants [124, 29, 77] can possibly contribute solutions to the fundamental global challenges of climate change and a growing (city) population.

At the same time, these ideas also come with scientific challenges and high demands to biology (in particular plant science), architecture, robotics, and engineering [43, 44]. Appropriate plant species need to be selected according to their speed of growth, their growing type (climbing, bush, tree, annual/perennial, average leaf size, etc.), and the accumulated knowledge about them (model plants). Plants differ in their reaction to light, mechanical interaction, and hormones. Also mutants of plants could be considered, for example, if their growth turns out to be easier to steer. The architectural challenges of a continuous growth process are much more complex, have many more degrees of freedom, need new types of design rules, and possibly even a new mindset opposing architecture that has a well defined endpoint in time. Plants in living architecture can be used directly as building material but also to change material properties of other, 'artificial' building material. For example, plants can be grown through other materials to make them stiffer. During the initial explorative period of our project we have identified braids as a methodology with overwhelming opportunities. Braided structures can be produced autonomously by robots at site, can be used as scaffolds, can be stiffened by plants, but we can also embed electronics, sensors, actuators, computational units, and robots into strips and braids. The braids can solve the problem of slow plant growth [49]. Instead of having to wait for decades to move into the living house, the house can start from an autonomously constructed 'dead' braided structure that is then successively substituted by grown alive plant material. We use generative and developmental methods to guide the growth and replacement pattern of these braided structures [151]. They combine environmental and internal sensory information and consider local and global requirements of the living architectural artifact. A braiding robot can serve as a construction robot only but it can also stay at the site as part of the living building to continue to produce braided scaffolds adaptively to the plants' needs and growth (similar to a self-assembly process [22]).

The requirements for the robots that steer plants and interact with them are also rather complex. The robots need appropriate actuators to provide stimuli that trigger the natural adaptive behavior of plants. In *flora robotica*, we use visible light to attract plants and far-red light to repel plant growth. Using light may be challenging in outdoor conditions but fighting the sun may not be required when working with blue light possibly supported by devices to shade parts of the construction. Options of mobile robots seem to require climbing capabilities that we do not explore in *flora robotica*. Instead, the robot design is simplified by keeping robots static while they can be replaced via user interaction. Actually, that is a suitable option given the slow speed of plant growth, hence, making replacements necessary only infrequently. This is in line with a long ignored alternative to standard robotics, namely the concept of 'slow bots' [4].

Sensing is an exceptional challenge in *flora robotica*, starting from sensing the mere presence of plants to measuring the plant's well-being based on sap flow and electrophysiology. Following the idea of phytosensing [85], we can use plants to report certain environmental factors, that may be difficult to sense with technological sensors. Then the challenge, in turn, is to sense the respective reaction of the plant. The control of plant-steering robots itself can be simple if only predetermined patterns need to be grown. However, the combined plant-robot experiments need to consolidate protocols and traditions from two very different fields. Even simple features, such as lab room temperature and light conditions, need to be selected wisely and need to compromise requirements of robots, plants, and human beings. The robot control gets complex once only certain percentages of desired biomass are determined by the user or once also the motion of plants needs to be controlled. In a recent paper, we describe our methodology of machine learning techniques (evolutionary robotics) to steer plant tips into desired targets [140, 51].

The philosophy of bio-hybrid plant-robot living architecture has a lot of potential and could be pushed further to having equal roles of plants and robots resembling a symbiosis (e.g., also the plants are allowed to request replacements of robots or to request actuation). An interesting research track could be to develop growing robots that behave similarly to plants [86, 87, 47] and one could even try to control plants such that they complete tasks that were previously reserved for robots. This could include grasping or to navigate plants towards connection positions and connecting building material by growing around them (alive plants as connections, similar to alive ants for stitching, [41]).

In *flora robotica* we focus on developing a generic basic methodology for a radically new field of plant-robot living architecture. We plan to showcase our achievements in a benchmark where we grow a small wall with two holes cut into it, where one hole is supposed to be a window (growth prohibited) and one represents damage and is to be regrown (see Sec. 4.3). Hence, we would like to showcase a living architecture with the capability of self-repair and continuous growth.

3.2.2. Plant science perspective on the natural-artificial "ecosystem"

Our efforts in *flora robotica* are focused on creating Societies of Symbiotic Robot-Plant Bio-Hybrids, where plants and robots interact with each other and possibly bidirectionally mutually shape their growth. Notably, "no plant is a lonely island too" [40], hence, we want to analyze an extended our view on *flora robotica* societies. A community of living organisms in conjunction with nonliving components of their environment forms an interactive system that is called ecosystem. Here we provide plants, robots, and artificial scaffolds as basic *flora robotica* components. Including living plants means that the system is generally open to other living organisms interacting with plants (see Fig. 78).

Pathogens and herbivorous. Pathogens and herbivorous are potentially the most crucial types of organisms that may also influence the artifact's material, structural, and aesthetic properties. Every plant species is prone to different species of pathogens and parasites. There are some versatile pathogens, such as *Botrytis cinerea*. Pests trigger complex plant responses to overcome pathogenic effects, which then result, for example, in retardation of growth and emission of volatile compounds. So both, pests and plant defense responses change the growth, structure, and morphology of plants.

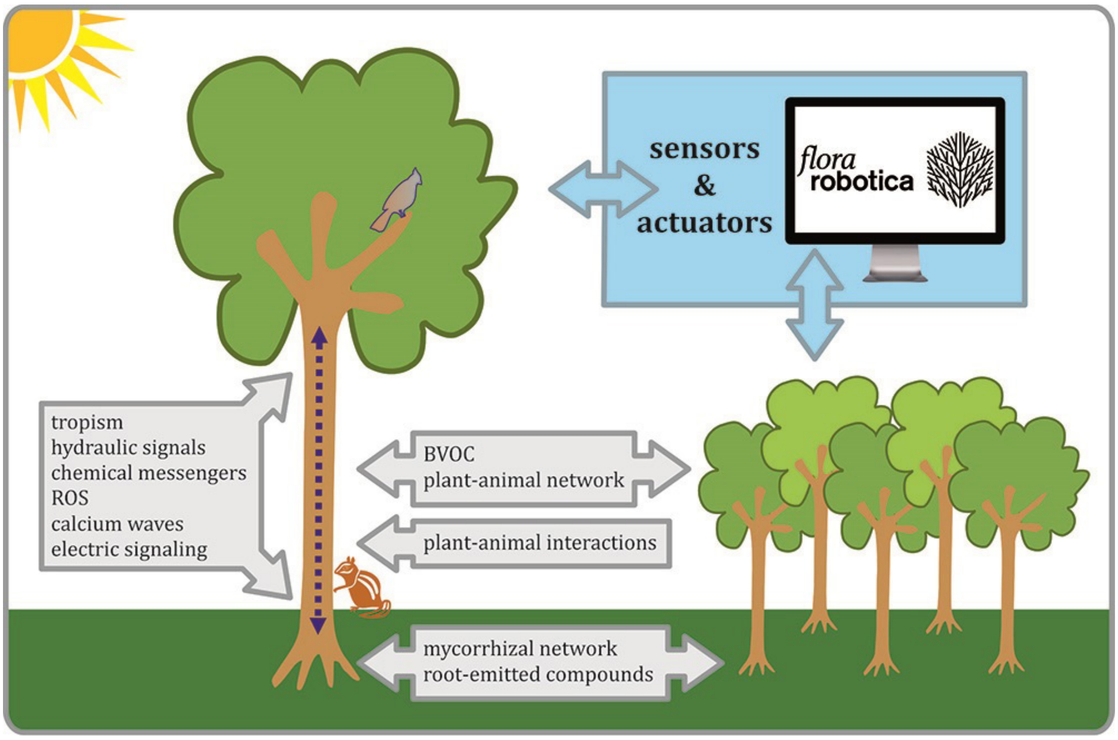


Figure 78: The schematic view on biological process that are important for establishing plant-robot communication in bio-hybrid systems [125]. Organismal and interorganismal signaling pathways are considered as crucial in bio-hybrid development, as well as progress in the field of advanced sensors, actuators, and controllers. All these tasks are part of *flora robotica*.

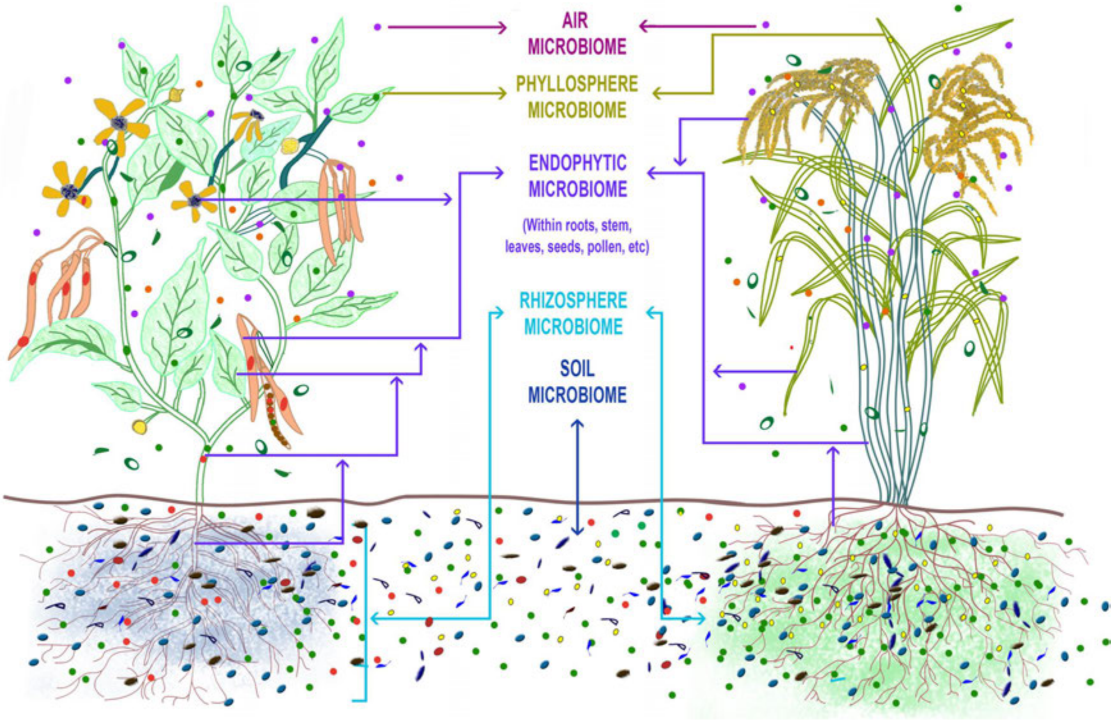


Figure 79: The 'Plant Microbiome' by Gopal and Gupta [40].

Biotic stress. Weeds also may influence plant growth, too. Especially in interaction with tree seedlings that exhibit great developmental elasticity but they could be overgrown by weeds. Moreover, plants interact with each other (for example, via soil or air by releasing chemicals), and not all collections of species enable plants to grow efficiently. All these sources of biotic stress have to be taken into consideration, especially while planning long term plants cultures. Outdoor cultures, as well as indoor or greenhouse plant cultures are prone to biotic stresses. Stable environmental conditions that are supporting fast plant growth (e.g., high humidity and temperature) may also promote pathogens or insect invasions. Challenges that are specific for greenhouses require usually more pesticides than what is needed for field cultures. In natural environments, complex interactions between different species may provide a more stable ecosystem than in the case of monocultures or greenhouse cultures. In the case of agriculture, pest management is well-known and based on parasitoides. We have to ensure that the chosen species and conditions limit undesired biotic interactions and risks need to be minimized (e.g., see Sec. 4.2.5 in D3.2 for central European tree species). For example, despite many interesting features, elm (*Ulmus*) is not proposed as an option of a tree for *flora robotica*, due to the deadly Dutch elm disease.

Microorganisms. Herbivores and pathogens are not the only organisms interacting with plants. It can be said that the "growth career" of a *flora robotica* system is not possible without microorganisms (see Fig. 79). An example is mycorrhiza. There is a considerable complexity and significance of plant interactions with soil microorganisms and endosymbionts (see Fig. 80). Providing growth-promoting soil microorganisms has been intensively investigated for agriculture.

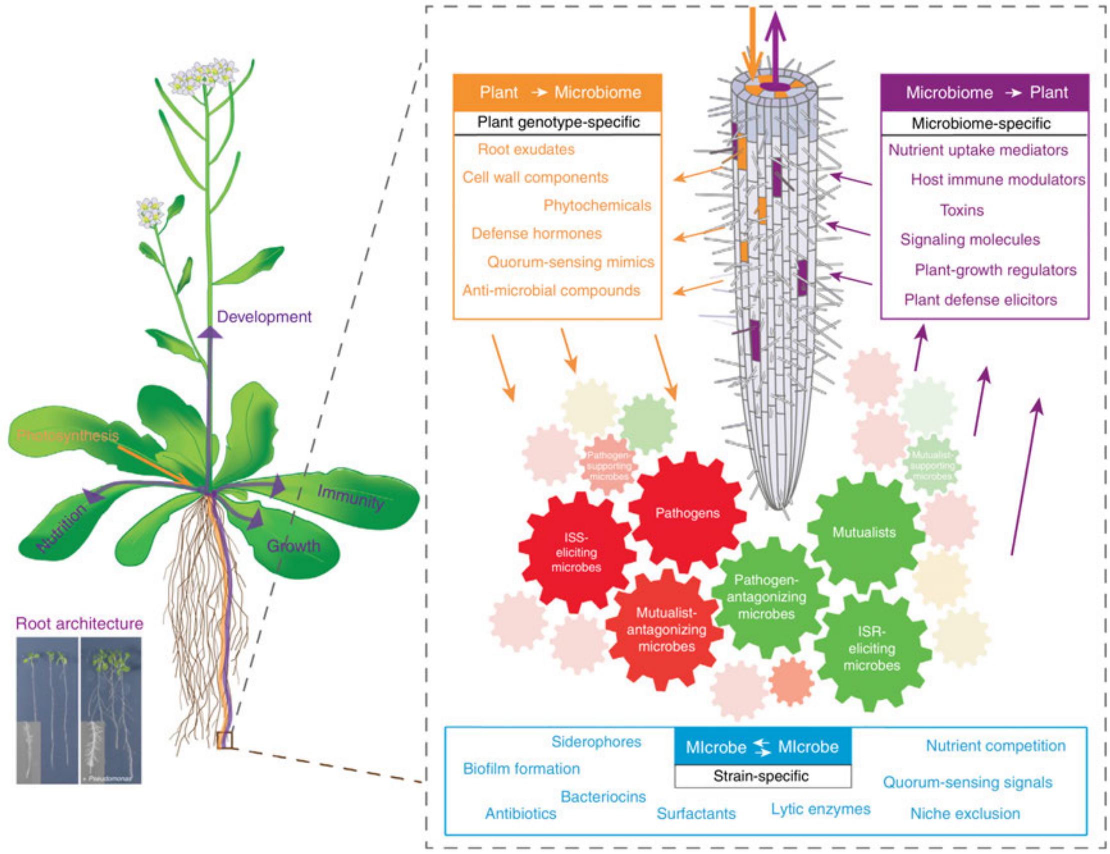


Figure 80: Schematic representation by Pieterse et al. [103].

Using beneficial microorganisms has to be considered in the case appropriate data is available for a certain species. The provided soil has to be configured specifically for certain plant species supporting an appropriate chemical composition, pH value, and beneficial microorganisms. Unfortunately, for most plants we lack data about the optimal soil.

Life and afterlife of plants and plant organs. Living plants as a building component have to be considered not only as continually growing entities, but also as dynamic, open systems that change structurally and morphologically in time. Many plant species are subjected to regular seasonal changes, such as leaves changing color and falling or flowering. Also mechanical properties of plant organs change during lifetime and due to the seasons. Annual plants, such as beans, do not disappear after dying but occupy space, have changing mechanical properties, and different aesthetic value. During a plant's lifetime we have to expect not only growth of already present organs but also the appearance of new organs due to branching or flowering. Certain plant organs, such as coniferous branches, may spontaneously be withdrawn. Lower pine branches, that are not longer exposed to sunlight, lose their needles and start to bend. Hence, we need to plan for the spatial reduction of a plant's architecture as a process when planning a *flora robotica* system.

Complex interactions and feedback loops with the environment. Living organisms sense and respond to environmental changes by adjusting their internal processes to overcome threats and to take advantage of changed conditions. Organisms successfully realize their developmental programs due to their plasticity. In addition, organisms actively shape their environment. For example, trees change light conditions for their lower branches, they change the soil structure, underground water conditions, and the ambient air. The activities of living plants change the originally provided conditions, such that future plant growth is not guaranteed. For example, the soil can be deprived of nitrates or the roots can overgrow in pots. Hence, environmental conditions have to be monitored continually, if we want to provide optimal conditions for plant growth. The physiological reactions of plants can be monitored to identify threads for the plant (e.g., using of Phytosensor for monitoring plants, see D1.3). Both, environmental and plant-physiological sensors are getting more important on long timescales and bigger spatial scales of our *flora robotica* system.

Plant-robot ecosystem. Artificial elements of the *flora robotica* system also influence the environment. The robotic nodes stimulate a plant's phototropism and we provide scaffolds, but there are also side effects. For example, the robotic elements increase the temperature (locally) due to waste heat. This heat influences plants and also other living organisms but may be of no harm. It is well-known that flowers generate complex heat patterns to attract and assist pollinators towards flowers. Hence, the waste heat of robotic nodes may influence effects of a plant's generative organs in close proximity. Side-effects of changed light conditions were discussed previously (see D2.2). Also the side-effects of inserting electrodes in plants are discussed (see D1.3). We expect most side-effects to be of minor relevance but we notice a need of the system to deal mostly autonomously with non-anticipated situations. This is, in turn, an omnipresent challenge in robotics, which is not yet solved. The advantage of the *flora robotica* system is that most actions are required only on intermediate and long time scales compared to standard applications of robotics. As a final backup solution, always a close-by human user can be asked to fix a certain issue (e.g., removing plant parts).

All above mentioned interactions and associations are going to be of more relevance with increased scales of space and time. Most of our experiments so far were finished within about two months. Long-term plants-robot societies come with qualitatively different challenges of interlinked growth effects, interacting organisms, and interactions of species.

3.2.3. Plant species

Given the architectural objectives of *flora robotica* require also bigger plants, such as trees. Societies of plants and robots are more challenging due to several reasons. The more complex architecture of trees, if compared, for example, with the common bean, makes plants shaping much more complex. Also longer timescales cause more potentially dangerous events of both biotic and abiotic origins (see Sec. 3.2.2). We prepared a list of several Central European plant species that were found to be useful species for outdoor applications of *flora robotica*. The requirements are diverse. We require strong wood that could support artificial elements or withstand a strong wind and good fitness in Central European conditions. Species of interest are climbing plants as they well suited for braided structures. In addition, some climbing plants and also basket willow are species that can be braided themselves. We have also added richly flowering plants due to their aesthetic impression.

Common hornbeam (name come from old-English words which mean "hard tree") (*Carpinus betulus*) is a well-known deciduous forest and ornamental tree with nice foliage. It reaches heights of 30 m and has moderate soil and moisture requirements. Hornbeam is a natural element of many European ecosystems and grows together with more dominant beeches and oaks. Hornbeam is often used to grow hedges. Wood of hornbeam is very hard and caloric, what makes hornbeam valuable for wood industry. In *flora robotica*, hornbeam could benefit in the project's realization by due to its aesthetic value and its plasticity in its architecture and hardwood, which is a strong structural material. Hence, hornbeam could be used as scaffold for robotic elements in bio-hybrids.

Beech (*Fagus sylvatica*) is a hardwood deciduous tree, which reaches even 37 m in European conditions. Big trees give a lot of shadow underneath, which has a big impact on a beech dominated biocenose. The beech does not require special light conditions or soil fertility, but it requires a good drainage of the soil and rather moist air. Wood of the beech is commonly used for manufacturing furniture and it is of great value. In gardens, beeches are often used to grow hedges. The Beech's nuts are nutrition for many animals and are also edible for humans either fresh, roasted, or salted. Forests composed of beeches belong to the most beautiful ecosystems in Central Europe and are well recognized in several cultures of European nations. Its straightness of the trunk and an elegant oval crown potentially make an adult beech tree a great contributor to *flora robotica*'s Social Garden.

Ivy (*Hedera helix*) is an evergreen climbing or ground-creeping plant, which can glue itself efficiently to almost any surface. Ivy is a shade-loving plant and growing slowly, but it is immune and hardly ever is infected by pathogens. As a climbing plant, ivy has a great plasticity in its direction of growth and it can glue to different surfaces, such as walls, other plants, and even artificial scaffolds. Ivy is useful also because of its thermal insulation properties for covered surfaces and expulsion of weeds from naked ground surfaces. Maintenance of leaves during autumn/winter season ensures that ivy-derived aesthetic benefits are available during all seasons.

Creeper/Grape ivy (*Parthenocissus tricuspidata*) is a climbing plant, which attaches to many different surfaces, for example, by utilizing secreted calcium carbonates from specialized pods. Its mechanism of attachment to surfaces is different from ivy and creepers, which could result in different possibilities of interactions with other robotic and botanical elements in our Social Garden. The creeper loses its leaves during the cold season, but in turn is colorful in autumn. This climbing plant can grow fast and has no special environmental requirements, but prefers sunny or moderately sunny places. Moreover, another advantage of the creeper are its berry fruits, which are a valuable source of nutrition for birds and other animals. The creeper can grow successfully even in polluted air. However, ivy and creeper may damage the surface to which they are attached.

Grape vine (*Vitis vinifera* or *Vitis labrusca*) is a fast growing climbing plant with woody trunk and famous fruits. It is one of the most important agriculturally dicotyledoneous plants in warmer areas of Europe. Due to its extensive root system it can survive in dry environments. Grape wine is now represented mainly by agricultural cultivators and almost no wild subspecies of grape vines have survived. The cultivation of grape vine requires cutting every year and support for cane and shoot, otherwise the plant will trail on the ground. The grape vine uses tendrils for climbing, so other plants or a braid provide good support.

Honeysuckle (*Lonicera caprifolium*) grows as twining bine, which could effectively overgrow braided structures (see D1.3). This species has great ornamental value, both flowers and fruits are aesthetically compelling. Gardening of Lonicera requires trimming during winter, especially in the first few years. Honeysuckle's canopy is so dense that it can be used for forming hedges or to form spatially separated compartments.

Fallopia (*Fallopia aubertii*) is the fastest growing climbing plant species in Central European climate. It is commonly used to efficiently covering vertical surfaces. To support the growth of fallopia, a grid or a twine is required and braided structures were shown to be advantageous for fallopia (see D1.3). Twines of fallopia may be braided as well as willow's twines.

Wisteria (*Wisteria sinensis*) is a fast growing climbing vine. It is a perennial, woody plant that is characterized by great diversity in its morphological types: wisteria can grow as climbing plant, but it is also possible to train wisteria to develop into a tree. Twining stems and branches finally get stiff, which gives a lot of opportunities for growing desired shapes with temporary scaffolds. Wisteria provides an aesthetic benefit due to its flowers, but also some danger, because of its toxic glycoside, called wisterin, which is found in all the plant's organs.

Basket willow (*Salix viminalis*) is native in Middle Europe as multistemmed shrub, which commonly grows at river banks and in marshes. This plant grows very fast and is tolerant to severe environmental conditions. The basket willow is a standard plant in energy forestry. Withies of the *Salix viminalis* are not branching twigs, which is utilized by basketry and can be used also in *flora robotica* braided structures. A growing willow can be guided to form entwined hedges and different structures, such as "living" chairs or benches. Not only by handcrafting or braiding machines braids can be produced, but also by robotic nodes. In comparison to bamboo, willow does not grow so fast, but its withies can be woven, which could be used to form new shapes and structures. In traditional cultivation of structural willow pruning is required, this fact is potentially challenging for our uses.The great link between braided structures and plants might be established by utilization of plants derived material which is biodegradable and organically growing. Hence, both living willow and willow derived wood may become important materials in *flora robotica*.

Gunii (*Eucalyptus gunnii*) is a medium-sized, shapely, fast growing, and evergreen tree originated from Tasmania. Gunii prefers well-drained, but moisture soil, and sunny locations. It is that species of eucalyptus that is most tolerant to low temperature (even down to -14° C). Different species of eucalyptus have been introduced to many areas worldwide, due to their advancement for forestry. Eucalyptus wood contains a lot of lignins and is commonly used for paper production. Worldwide eucalyptus cultures have an ecological negative impact. Eucalyptus mono-cultures degrade the soil and are a source of dangerous fires. However, these negative environmental influences are related to eucalyptus mono-cultures only and would not occur under multi-species conditions in our social garden. In addition, gunii has an excellent mosquito repelling property. Gunii is also a source of oil containing antimutagenic, antimicrobial, and antioxidant agents. This oil is volatile, so it can probably provide advantages also for social garden visitors, for ex which suffer from asthma.

Bamboo (*Phyllostachys aureosulcata 'Spectabilis', Phyllostachys flexuos, Qiongzhuea tumidissinoda, Fargesia denudata*) are a subfamily of Poaceae and are an evergreen woody grass. Bamboo is known as the fastest growing plant on the Earth (max. almost 1 m / 24 h). Bamboos are an important source of wood and food, especially in Asia. The growth of bamboo is columnar, based on activity intercalary meristems, and hence different from growth of dicotyledonous trees. Bamboos arise from underground rhizomes and they reach their maximum height in a short time and this height is then maintained for many years during a bamboo's life. Bamboos are also more and more common ornamental plants in European gardens, although the dedicated care of bamboo rhizomes is required in order to limit expansion. Shaping a bamboo is more challenging than shaping dicotyledonous plants, but would be useful in providing fast growing plants with great mechanical properties. Moreover, bamboo shoots are edible and are a healthy source of fiber, vitamins, and microelements, which may assure additional benefits for human users.

Rhododendron (*Rhododendron ferrugineum*) comes from the Alps and Pyrenees and is a common plant in European gardens. It is an evergreen plant, which usually grows up to 1 m and is characterized also by big beautiful flowers. It can resist low temperatures, but rhododendron requires wet soil.

Midland hawthorn (*Crataegus laevigata*) is a small tree or shrub, belonging to *Rosaceae*.

Hawthorn has a lot of pretty flowers in May and June similarly to roses. Hawthorn does not require soil of particular fertility and could grow even in polluted areas. This species is used for making hedges and hedges formed by hawthorn are almost impossible to pass through. Fruits and flowers of this plant are valuable sources of substrates for traditional medicine. Hawthorn could be a good additional medium-size plant for our social garden.

Magnolia (*Magnolia grandiflora*) is a common ornamental plant in worldwide gardens. It is a medium-sized or big tree (up to 20 m), known for its large and beautiful flowers. Magnolia prefers fertile soils and exposition to sun. Magnolia's wood is hard, heavy, and is used also for timber. Astonishing magnolia's flowers are a simple and effective way to communicate the idea of "beauty" to people.

3.2.4. Plant motion and tropisms

Perhaps contradicting common perception, plants show a remarkable diversity of movements. Apart from passive propagules (detached pieces riding external forces) and motion due to purely physical processes [e.g., hydro-responsive curling in the resurrection plant, 107], there is a plentitude of physiologically controlled *active* growth and motion responses. *Active* plant movements can be grouped into:

1. autonomous, endogenously controlled movements;
2. externally triggered non-directional responses (i.e., *nastic* movements), where stimulus location is irrelevant for response; and
3. externally triggered directional responses (i.e., *tropisms*), where stimuli location determines the direction of growth and motion.

Of the autonomous movements, the most universal is circumnutation, which occurs in elongating tissues of all plants. This behavior, whereby tissues wind around their mean growth direction, is most notable in climbing plants that wind around a support, such as the common bean or morning glory [94, 90, 8]. This basic motion interacts with other motion behaviors, especially irreversible tropisms involving growth. *Nastic* movements are typically very fast and reversible responses where direction is incidental, such as the closing of a venus's fly trap regardless of the excitement direction [42]. Because of the context of applying robot-organism interaction to construction, we focus on the directional *tropisms* of plants, reviewed below. In natural settings, many of these responses occur simultaneously, with the strength of each response weighted differently according to species, developmental stage, tissue and situation.

Tropisms are directed growth responses guided by stimuli and enacted through the plant hormone auxin. Plants react to a variety of environmental cues with tropic movements, particularly at the roots [122, 138, 65]. Tropic changes in growth direction occur by redistributing concentrations of auxin, triggering anisotropic growth and thus inducing curvature. Plants employ gravity as a primary spatial cue to orient their growth, via *gravitropism*. Stems generally grow against the gravity vector, while roots grow along it. Lateral roots, branches, or leaves often keep the gravity vector at a constant angle to their growth direction. Gravity is sensed in regions near growth tips (of shoots or roots) via subcellular statoliths [46], ultimately leading to anisotropic expansion and division of cells, causing directional re-orientation [6]. Even small gravitational forces (as little as 0.1 g) can produce profound effects on growth patterns [cf. wheat seedlings, 101].

Plants react and adapt to mechanical impacts on all scales [45, 92, 71], from stretch-activated ion-channels in cell membranes to wind-swept trees minimizing surface of exposure [131, 33].

Although gravity is a type of mechanical stimulus, the sensing and signaling pathways for gravitropic responses only partially overlap with those for other mechanical impact responses [134]. In general, mechanical forces provide plants with information about their environments and themselves, allowing for adaptive behavior [113]. *Thigmotropism* (touch-guided growth) can readily be observed in root tips growing along the edge of dense soil clumps, assessing and following the penetrability of the material while still generally satisfying their gravitropism [93, 84]. Another thigmotropic mechanism, common in climbing plants, helps tendrils coil quickly around objects they touch using ionic signaling and differential turgor-changes. If the stimulus is only transient, tendrils can uncoil again. However, if irreversible responses (growth and lignification) have already occurred, the coiling can no longer be undone [12, 123].

Plants perceive light wavelengths from UV-B to far-red (between 280 and 750 nm), incorporating it in a number of ways. For example, the incident direction and duration of photoreceptor exposure is used to help time key developmental decisions and to continuously direct growth to exploit the most promising local light situation [53, 31, 99]. Additionally, light in the visual spectrum (between 400 and 700 nm) is a necessary food staple of plants and is absorbed via photosynthesis [52, 114, 115]. Concurrently, phototropism directs growth trajectories relative to the incident angle of light, for which the typical sensing mechanism is well-characterized. Blue light (and to a lesser extent UV light) excites membrane-bound proteins, relaying the signal to the cell or to responding tissues further away. This again leads to the same redistribution of auxin concentrations, and subsequently anisotropic growth [18, 73, 13]. Phototropic responses and their intensities vary largely across species, developmental stages, and tissues. For instance, some climbing plants will temporarily employ *skototropism* (growth towards shade) to find a support to climb, by growing towards the darkest spot, but not necessarily away from the brightest. There are also reversible directional responses to light, such as the light-stimulated movement of leaves [55, 145] or the famous heliotropic movement of young sunflowers before the flower opens [70].

Being photosynthetic organisms, actively avoiding shade is a major benefit to plants. They have evolved complex strategies to manage shade or potential shade by harnessing their full arsenal of light receptors [28]. These strategies include the avoidance of projected future shade from nearby competitors by triggering the well-researched shade avoidance syndrome (SAS) [102]. This response is triggered by spectra enriched in far-red [and possibly green: 141] light, a good indicator of the proximity of chlorophyll-bearing organisms. Mechanical stimulation and plant-emitted volatile chemicals can also feed into this response [102, 31]. It usually results in elongated stems and in petioles with reduced branching and root growth. Meanwhile leaves tilt upwards (*hyponasty*) in an attempt to outgrow competitors. Much less is known about shade-tolerance mode, which is employed by plants growing under a dense canopy to cope with long-term shaded conditions. Typically this response leads to an increase in specific leaf area (SLA), an optimization of photosynthesis for low-light conditions, and greater physical defense of leaves [39].

Chemotropism (chemically guided growth) has long been known in roots, which sense a plentitude of chemicals and are seemingly aware of local and global needs [7]. In shoot tissues, chemotropic growth has been shown in the parasitic dodder, as it seeks and selects host plants in a dark environment [116, 34].

Plants control which tissues follow which environmental cues, as well as the timing and magnitude of response. In this way, a certain stimuli can influence or fully override the direction growth would otherwise follow, according to factors like nutritional status [138]. The development of a climbing bean is an illustrative example of this concept. First, the germinating bean shoot grows against gravity, but towards (blue) light. Soon, autonomous circumnutational winding sets in, allowing the plant to use its sensing machinery to assess the environment in much higher spatial resolution [135], while increasing the odds of hitting and encircling a support. If that occurs, thigmotropic cues help the bean wind around the structure, while the other tropisms are still present. More favorable light regimes allow the bean to climb supports at more horizontal slopes, while both light and gravity positively influence the circumnutation radius. Finding a support triggers a change in development as the plant is relieved of the need to mechanically support itself [12, 34, 94]

All of these processes and sensing strategies are at the disposal not only of herbaceous species like bean, but of self-supporting woody species. Such species have been used in the domains of architecture and plant shaping (see Sec.4.1.1) to build up adaptive living support structures over years or decades. The guidance of woody species through the stimuli and tropisms described here, rather than through manual manipulation, could be investigated. Beyond utilizing the plants' natural growth and motion behaviors, the genetics of plant development are increasingly becoming understood [27], opening routes to 'programming' plants for functional applications like construction.

3.2.5. Shaping plants

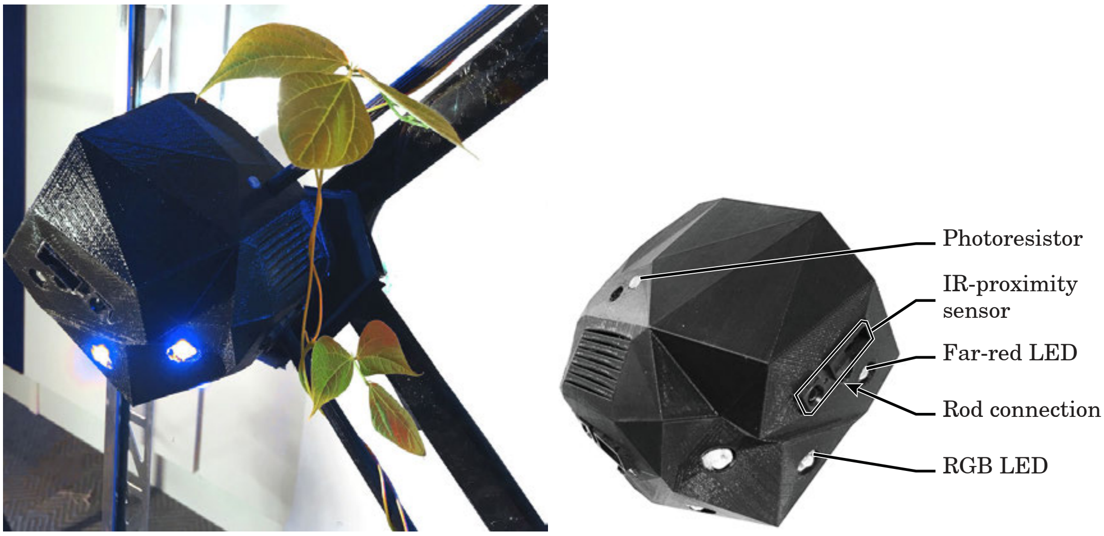
In *flora robotica* we want to develop a self-contained bio-hybrid system that keeps robots, sensors, and plants also spatially close together. This way we have a higher potential to fully integrate the technological components into the grown structures, the sensors actually require vicinity in most cases, and we may even hide the robots behind plants. Similarly, the interactions between robots, sensors, and plants are closer and assigning them equal roles may be easier to achieve. Hence, the robots and sensors are put initially on the braided structures until the plants grow strong enough to hold and carry them.

In our development of robotic nodes (see Fig. 81)that steer directional plant growth, we require integrated concepts of sensing (detecting nearby plants and plant organs) and actuation (in the form of providing appropriate stimuli to the plants). Both requirements are challenging. Plant organs, such as the shoot's growth tip, can have geometries and surfaces that are unfortunate for sensors (small, round, light absorbing). The executed stimuli need to be of correct intensity, as too little triggers no reaction in the plant and too much can stress or even kill the plant. In addition, the robots need to fit into our overall motivation in terms of architectural function and need to be compatible with the braiding approach.

Our distributed robotic nodes are incorporated within the braids. They steer and shape growth patterns of shoots as the plants mature along mechanical scaffolds. These plant-shaping robots interact with the self-organizing behaviors of plants by robotically providing stimuli that trigger directional growth and motion responses.

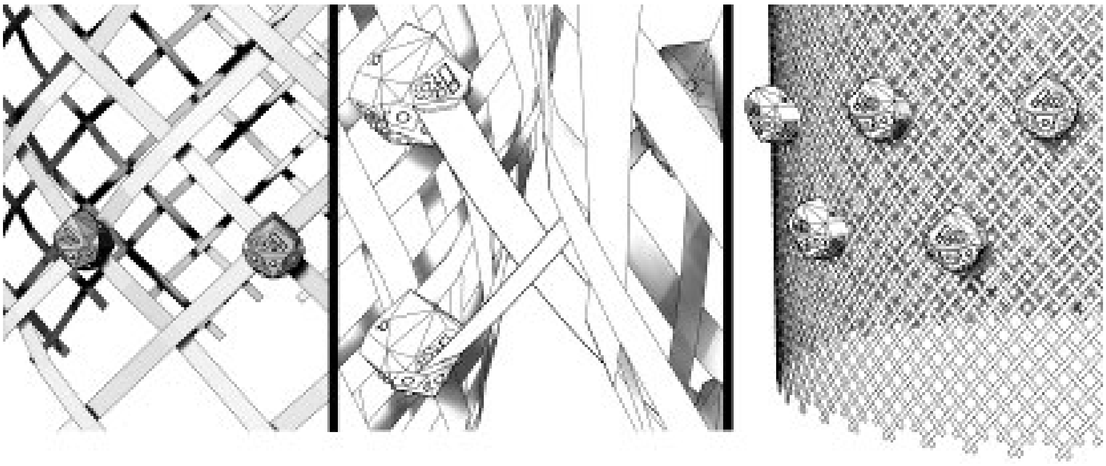
LED actuators in the robots can either trigger a phototropic response and attract the plant, by providing blue light, or can trigger the plants shade-avoidance syndrome, by providing far-red light.

Though plants can use the full visual spectrum of light as photosynthetic food source, their irreversible growth towards favorable light conditions—governed by the phototropism behavior—is triggered specifically by blue light and UV light. Therefore, while the plants are kept healthy and fed by ambient red light in our setup, a concentrated source of blue light is able to reliably attract the plant and steer the direction of growth. The plants shade-avoidance behavior is more complex than the relatively straightforward phototropic response. The response is triggered by high concentrations of far-red light (an indicator in natural environments of neighboring plants in close proximity), but can also be impacted by mechanical stimulation and emitted chemicals. When the response occurs, it may cause a combination of behaviors, including both repulsion of growth direction and faster stem elongation. IR-proximity sensors detect the presence of an approaching plant growth tip and photoresistors detect the actuation state of neighboring robotic



(a) robotic node and growing bean

(b) sensors and actuators of the robotic node



(c) concepts of robotic nodes in braided structures

Figure 81: The robotic node, its components, and visualization of the concept of robotic nodes in braided scaffolds.

nodes.

Using a weighted arithmetic mean approach, we are able to use the IR-proximity sensor to reliably detect approaching plant growth tips as far away as 5 cm. The sensor does not interfere with the shade-avoidance behavior actuated through the far-red LEDs, as no critical wavelength overlap occurs at distances greater than 2 mm from the sensor. We use a distributed approach to control the robots, so that their artificial self-organization might hybridize with the natural self-organization of the plants.

Experiments conducted so far demonstrate the ability of the nodes to shape climbing bean plants, steering the plants binary decisions about growth directions as they navigate a mechanical

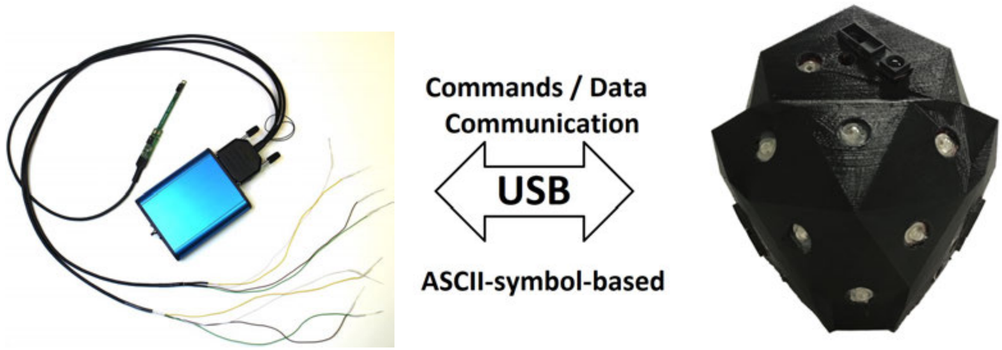


Figure 82: Phytosensor System connects to the robotic nodes for plant shaping, and communicates with it through ASCII-symbol-based protocol.

scaffold.

3.2.6. Phytosensing

To create a truly bio-hybrid system, we need to provide two-sided communication between plants and robots, robots and plants, plants and humans. Interfacing with plants is challenging because of their complex biochemistry, their slow responses, and slow reactions to responses. While the well-being of the plant, its physiological parameters, and its growth mostly depend on environmental conditions, that are easily monitored, we need to gather and provide information about the plant's direct responses and reactions to certain stimuli and environmental conditions. Plants are well-known to have a sophisticated and fine ability to sense and respond to changes of environmental parameters and external perturbations.

There are already several generations of Phytosensor System developed and used in *flora robotica*. The system and used sensor approach presented and described in D1.1, D1.2, D1.3 and D2.1. The Phytosensor will be integrated into the *flora robotica* benchmark in order to provide the plant feedbacks to robots. Phytosensor itself act as sensor-actuator frond-end for higher level computer device. The USB 2.0 interface is used for powering and communication with 'outside world' (see Fig. 82). The interface and protocol for exchanging commands and data between Phytosensor and PC has been already developed. As well as Client program *CYBRES EIS Client* for Windows OS. Client program provides all required functionality: configure the device, set the number of Phytosensor parameters, receive and save the measurement data into the files, process the data, plot the graphs, save the images, etc.

3.2.7. Supporting plant health

In addition to robotic nodes for steering and the Phytosensor System, there are external sensor modules that we call Global Environment Monitors (GEMs, see Fig. 83), used to partially automate the gardening tasks needed to support plant health, particularly in indoor setups. GEMs are equipped with temperature-pressure-humidity sensors, RGB color sensors, soil moisture sensors, and water pumps. They are capable of monitoring the room environment where an indoor setup grows and providing the plants with water when required. The GEMs upload their sensor data and log files, and run a reply server that can answer specific requests (e.g., the latest measurements of a specific sensor).

Figure 83: The Global Environment Monitors (GEMs) are comprised of several sensing, actuating, control, and logging functions, including (from left to right) water pumping, sensing of moisture, temperature, and humidity, and sensing ambient light conditions.

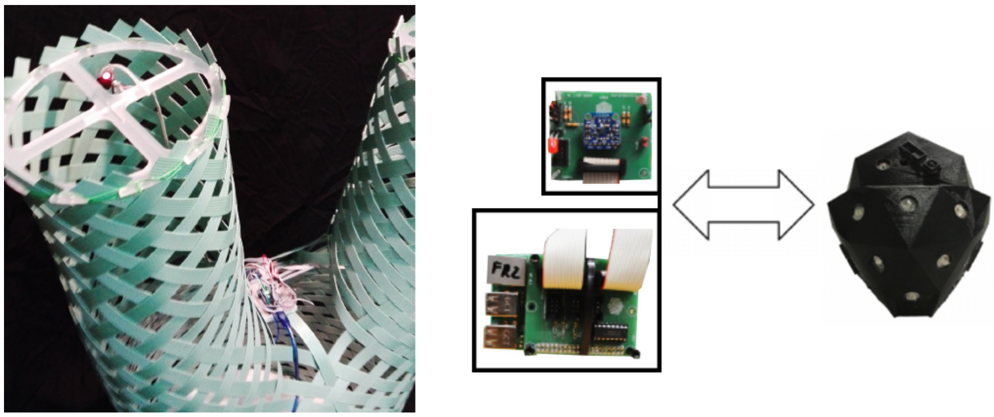


Figure 84: The RaspiNet, the hardware running the VMC, connects to and communicates with the nodes for plant shaping.

In experiments conducted so far growing plants on a scaffold in a environment without any sunlight exposure, 45 W 'Erligpowht' LED plant growth lamps have been added to the system to provide sufficient amounts of constant monochromatic red light, assuring the survival and health of the plants during the experiments. The need for such growth lamps is dependent on the specific needs of an indoor setup.

3.2.8. Fabrication and actuation of scaffold

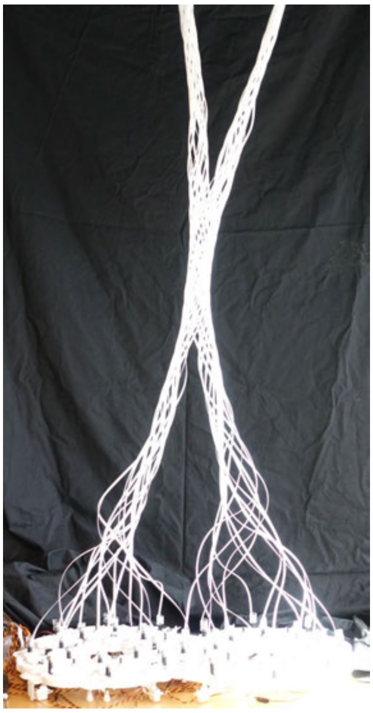
We use braids as (temporary) architectural artifacts in the form of scaffolds, surfaces, tubes, and tree-like shapes to initiate the bio-hybrid system before plant growth of any considerable amount has happened. To create a braided structure, multiple continuous filaments are interlaced through a structured pattern. We have developed a modular robotic system that can interlace filaments through various patterns, resulting in various topologies of braids. This robot can be used to pre-fabricate braids or to braid, for example, scaffolds at the site possibly directly adapting size and branching of tubular shapes to the currently growing plant. These growth patterns can be influenced by input from sensors and robotic nodes for plant shaping mounted

Figure 85: An example VMC structure in simulation (inset image) to guide the branching of braids and the number of filaments in each branch. This sketch shows a braided scaffold that is attracted and growing towards the space at the right side because it is infrequently occupied by furniture or people.

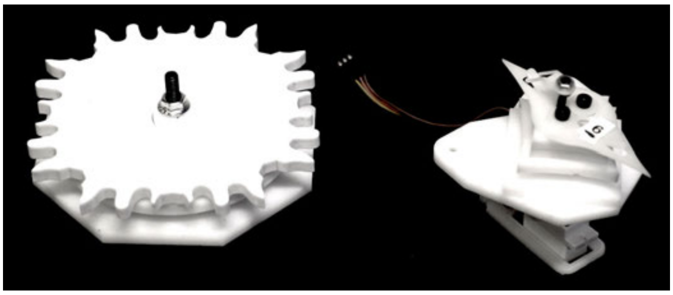
on the scaffold in a generative process, by the Vascular Morphogenesis Controller (VMC). The hardware for running the VMC *in situ* connects with the robotic nodes for plant shaping (see Fig. 84).

The VMC algorithm (see WP2) was developed based on inspirations from decentralized decision-making mechanisms of branch development in plants. It combines the predetermined rules of branching with global and local sensory information from the environment and leads to a self-organized process of growth for physical structures. When scaffolds are mounted at the site and equipped with robotic nodes and sensors, the VMC algorithm running on the robotic nodes can suggest to the braiding robot where and when the branching/fusion of the scaffold should happen and how many of the braiding filaments should go to each branch depending on the current status of the scaffold and the environment (including the plants and humans). Figure 85 illustrates an example braided scaffold where the development of its structure is guided by VMC.

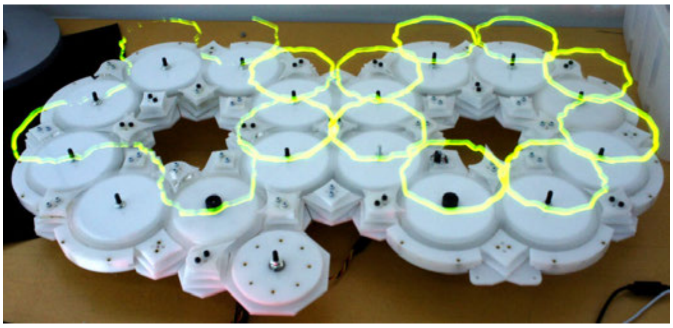
The braiding robot system is composed of a software control side and a modular hardware side connected over an integrated hardware-software circuit with sensing and timing control. The hardware consists of two main types of modules: driver modules and switch modules as seen in Fig. 86(a). These are laid out on a flat surface and by assembling them one can create strings, circles, and matrices that together compose the braiding machine (see Fig. 86(b)). In



(a) Filament is connected to dispensers which are driven by the modules to create braided structures.



(b) Two types of modules make up the braiding machine, driver module (left) and switch module (right)



(c) 16 Modules assembled as two circles of each 8 modules. The circles are connected over two driver modules, and share one switch module.

Figure 86: The modular braiding robot design.

addition to the two module types, other inactive support modules have been designed. The modules can be assembled in different configurations corresponding to the desired braid patterns and topologies. When assembled the modules create a self-intersecting, concave rail system that allows to systematically carry material dispensers by the modules in cooperation. The braided structures are created when many such material dispensers simultaneously extrude filaments while moving in intersecting pathways (see Fig. 86(c)).

A software side of the system both calculates and controls the collaboration between modules, and ensures that carriers do not collide. This software provides representations that help the operator of the machine both to verify the collaboration and to control loading and unloading of dispensers.

3.3 Projecting the Growth Career in simulation with IGP

To project the possible growth futures of the holistic *flora robotica* system, we integrate the various project models into a unified simulation setup, using the method of Integrated Growth Projection (IGP). The IGP is under development, and the implementations and results described here use the IGP in its intermediary stage, as described in D2.3. Future developments and results of the IGP, including combining it with evolution and with Interactive Evolution, will be reported in future deliverables D2.4 and D3.3.

3.3.1. Modeling braid fabrication

Here, we expand on the description of the IGP implementation in D2.3, giving more details about the integration of models concerning generation and fabrication of braid.

Generative design In this example workflow, a generative input is given to the braid solver. As an example of such an input, we use the Vascular Morphogenesis Controller (VMC) to supply a macro scale graph that grows over time based on environmental conditions. In a case where a braided artifact is manufactured robotically in situ and sensors are embedded in the physical braid, a controller like the VMC could be used to guide the shape of the braid in a way that is adaptive to dynamics of the environment (and provides behavior diversity [150]). Therefore, in this workflow, we use a simulated VMC graph output to generate a mesh topology for the braid solver (see Fig. 88).

This method is meant to be used with the braid machine fabrication process. The VMC input necessitates a solver to automate the integration of constraints for fabrication by the braid machine. To guarantee that a generated braiding pattern can be fabricated by hand or with a braiding robot, the underlying mesh has to have all the faces marked with a direction pointing in the fabrication direction. A macroscale directed graph approach was developed to generate meshes following this constraint (see Fig. 87). The graph serves as a scaffold for the mesh tiling, and has to comply with several constraints to satisfy the fabrication method and mesh generation routine.

Figure 87: Example mesh solution (center) from a weighted macro scale directed graph topology (left) and the eventual result from the braid solver (right).

Generating fabrication instructions In this example work-flow, a braid result from the solver is used to automatically generate fabrication instructions for distributed robots, centralized

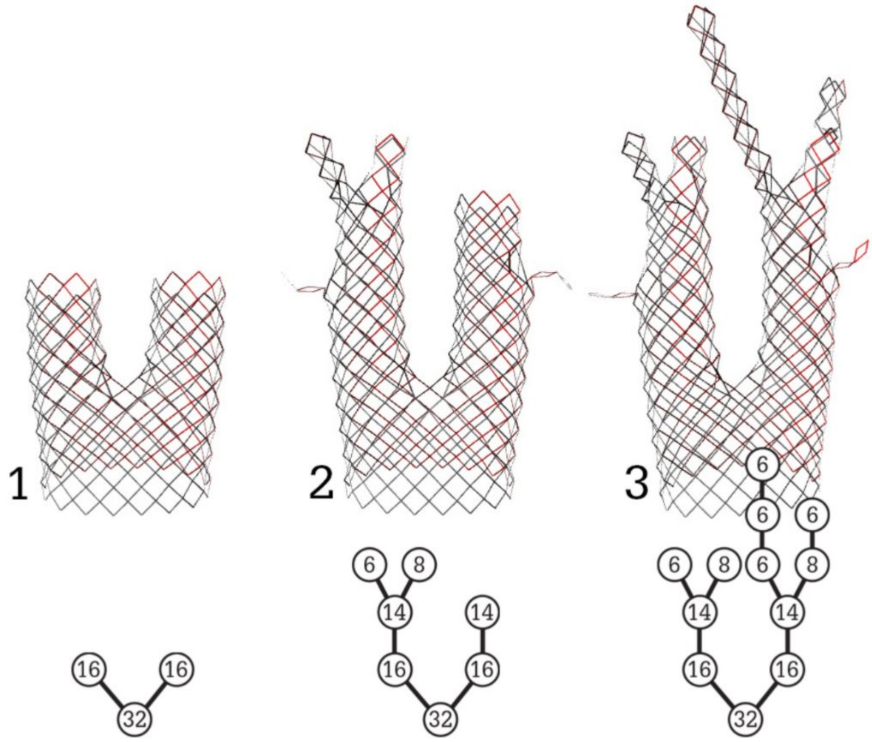


Figure 88: Three example time-steps from the simulated growth of a VMC graph, and the braided artifacts resulting from those graphs when interpreted one-to-one, with number of filaments defined as a parameter at each node of the VMC output graph.

robots, or hand fabrication. In this example, we look at hand fabrication of a simple 12-strip bifurcating braid. We developed a method, firstly, to generate a low-level graph representation of the braid's organization and, secondly, to interpret that graph into instructions using a string replacement dictionary. The low-level graph represents the braid as a series of connections, in which each intersection of braid strips receives a unique ID, and the under or over condition of a strip is indicated by a sign attached to the intersection ID. In order to generate this low-level graph, an agent beginning at the beginning of each strip walks it until it finds a new strip intersection point. Once it has found an intersection, it waits there until it sees that its neighbors have also found intersections. At this time, the agents each log their newly found connection, and resume walking along their assigned strips. This process is continued until the agents all find the end of their assigned strip. After the low-level graph is produced, their connections are interpreted through a dictionary into instructions for hand braiding (see Fig. 89). These instructions could potentially be implemented into a user interface and combined with a braid visualization to interactively show the intended result of each instruction step.

For use with the braid machine This method can also be used with the braid machine fabrication process, by providing one of the four inputs taken by the braid machine software (described in D1.3). The braid generation process also is extended from its reported status in D3.1, and now encompasses not only 2D braid, but is generalized to also encompass 3D braid,

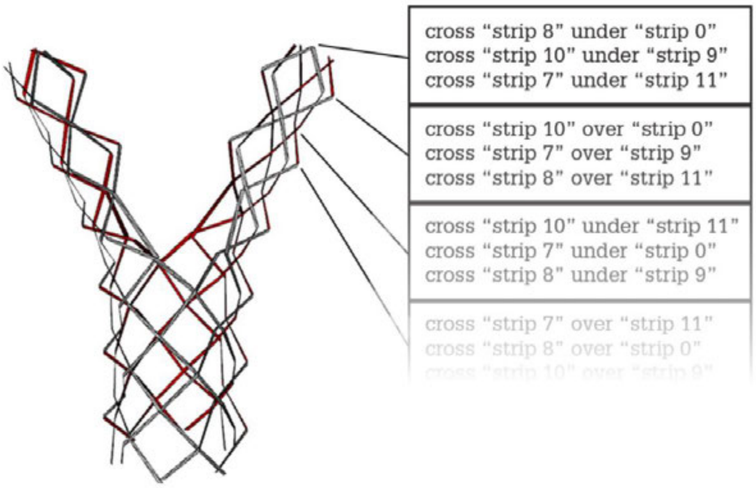


Figure 89: Example instructions for hand braiding, generated using a low-level graph representation interpreted through an instruction dictionary.

including the type of 3D braid that can be produced by the braid machine (see Fig. 90).

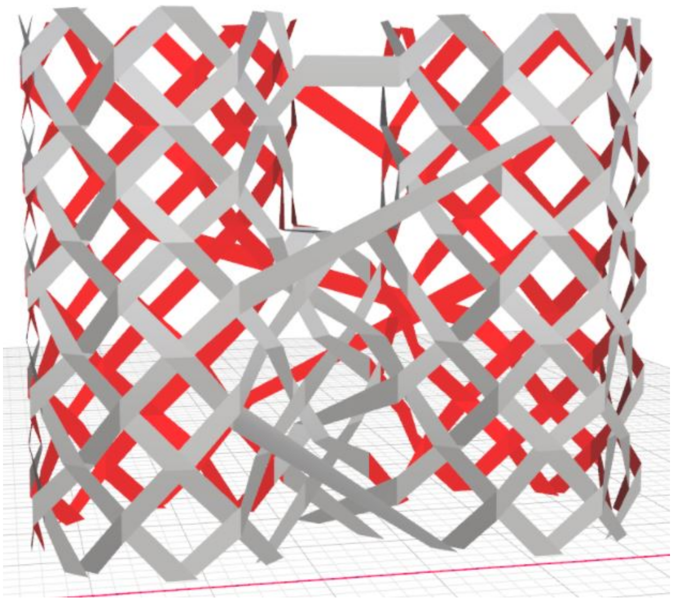


Figure 90: 3D braid able to be fabricated by the braid machine, similar to the 3D braid described in Sec. 2.4.1.

3.3.2. Using the 'Integrated Growth Projection' (IGP) to project an example growth

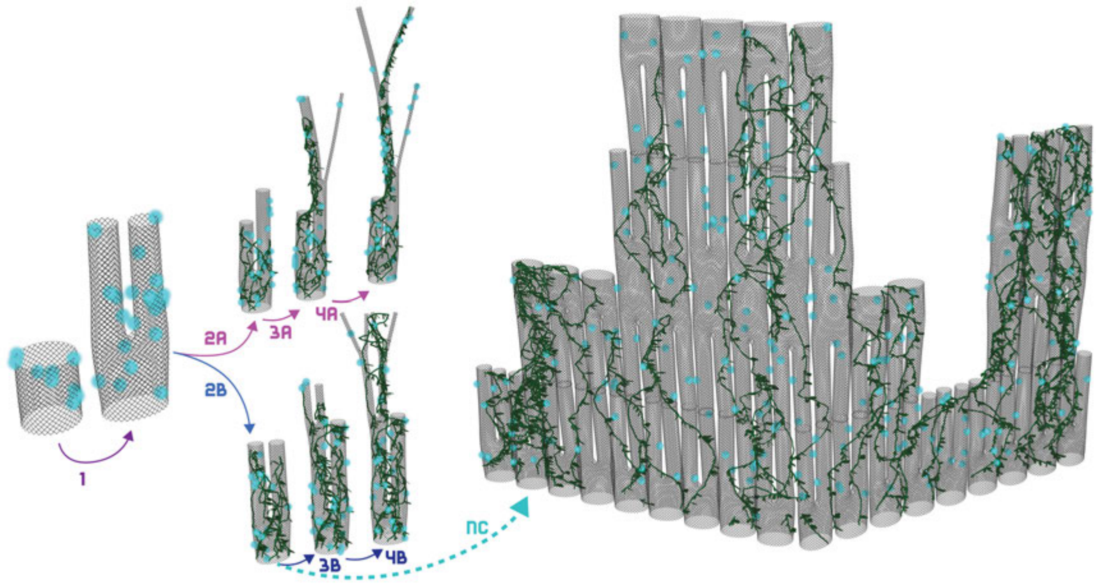


Figure 91: A diagram showing IGP results for possible growth career steps that a single *flora robotica* instance could take, first in very early steps (left), and then in one much later step (right) where a recognizable architectural space has emerged.

As can be seen throughout this document, there are a great deal of practical constraints on the artifacts made, in any real-world implementation of the holistic *flora robotica* system. Here we present an IGP result, visualized with all the additional categorical components of *flora robotica*, to approximate a possible example growth that could realistically be produced by the hardware and mechanics at their current state of development in the project (assuming sufficiently large quantities of hardware and a sufficiently long growth period). The IGP setup used in this projection is the version at the phase of development reported in D2.3, incorporating VMC, nodes for plant shaping, braid, and plant growth. The process undergone in this intermediary development phase of IGP is briefly illustrated in the diagram in Fig. 91. Of the IGP setups described in D2.3, the one used here to define the braided structure is the hybrid approach, where pre-relaxed mesh models of braids are recast as a dictionary of modules. The following are the practical constraints taken into account, beyond the standard functioning of the IGP, in order to project an example growth that is feasible to construct with the specifications of the real-world system:

- **Growth Career:** In the context of being considered a part of an ongoing growth career that is influenced not only by the software, hardware and plant components, but by the sensed activity and feedback of human occupants (see Sec. 3.1 and 3.2.1), we consider the process by which an artifact grows. Often in the architectural envisioning (see Sec. 3.1), and indeed throughout the project, it is considered or assumed that as a *flora robotica* instance grows and its performed functions continue to change, the functions of new growth will be defined in response to the most-up-to-date information from the environment. This assumes or implies that portions of the artifact close to the ground are constructed first, and upper parts constructed later. Practical growth constraints also support this specification, as once a plant has attached itself to a part of the mechanical scaffold, the scaffold cannot change position drastically, or it will kill the plants, pulling it up by its roots. This is because, as the plant grows, new material is added at the tip, not at the base. In order to succeed in growth symbiosis, we then assume for now that the system's artificial growth must follow the same process. This may seem to be a minor nuance to focus so much on, but it has important implications for the braid machine, detailed below.

- **Mechanical braid type:** Within this document, the type of braid that was determined to offer the best combination of mechanical properties and possibility to be produced by braiding machine was triaxial braid. Specifically, such braid comprised of triaxial filaments that are significantly more stiff than their biaxial counterparts (see Sec. 2.4.2).

- **Braid surface topology:** In this document, a wide variety of possible braid surface topologies are reported (see Sec. 2.2.2), especially for triaxial braid. Of those able to be produced autonomously by braid machine, we limit ourselves to triaxial braid the does not incorporate any irregular cells, and that does not require its filaments to be manually rearranged after braiding in order to achieve the desired topology. We also consider the braid surface topologies that offer added stiffness. We therefore select topologies where tubular braid bifurcates and re-merges repeatedly (see Sec. 2.2.2). We also assume that such braids will have an oblong cross-section in the merged portions, at the braid machine often produces braids displaying this feature (see Sec. 2.4.1).

- **Braid machine:** Categorically, the braid machine (see D1.3, and Sec. 3.2.8) works like an extrusion-based additive manufacturing device—that is, the braided material the emerges first, is the material that will be furthest away from the braid machine at the end of manufacture. When considered in combination with the constraints of the Growth Career, above, it follows that the braid machine should be situated on top of the braid it is producing (see Fig. 93, blue circle), with the first filament ends issued from the machine being the ones affixed to the ground plane. In this way, the braided structure will grow in the same way the plants do: with new material being added at the growth tip, not the base. This strategy could potentially pose problems, regarding the mechanical stiffness needed to support the weight of the braid machine. However, the use of triaxial braid as a type should lend sufficient stiffness to support the braid machine, which is not especially heavy. We assume such a setup for this example growth projection.

- **Plant health (GEMs):** The Global Environment Monitors include hardware located at several locations around a soil bed (see Sec. 3.2.7), and can service multiple plants. This may be implemented in other fashions in future experiments, but for now we take this setup as a specification, and concentrate the points of plant roots in a series of soil beds (see Fig. 93, yellow highlight).

- **Robotic nodes:** In this case, we specify the robotic nodes present on the braid to be indicative of all three interconnected hardware modules: robot nodes for plant shaping (see Sec. 3.2.5), modules for phytosensing (see Sec. 3.2.6), and RaspiNets for running the VMC software (see Sec. 3.2.8).

- **Structural viability of plants:** In order to increase the likelihood that the plants will reach a stage of maturity where they will be able to perform the primary structural role, we follow the approach of incorporating soil beds at multiple heights along the braided structure (see Fig. 93, red circle), rather than exclusively at the ground plane (see Sec. 4.1.2).

- **Architectural use cases:** We incorporate the following features into the artifact, meant to support architectural use cases for human occupants: wall, corner, seat (see Fig. 93, green circle, and Fig.94), window (see Fig. 93, purple highlight), door (see Fig. 93, pink highlight), and mountings for possible additional of standard mechanical elements for a second-story floor-plate (see Fig. 96).

To add even further stiffness to the braided structure—enough that it could feasibly be considered for the support of self-weight and live loads in a multi-story structure—we carefully generate the patterns of bifurcation and merging, such that they rotate their bifurcation directions periodically (see Fig. 95). This forms a thick braided wall that not only provides substantial stiffness, but provides ample room for the incorporation of standard functions in a building's wall system, such as thermal insulation and utility infrastructure.

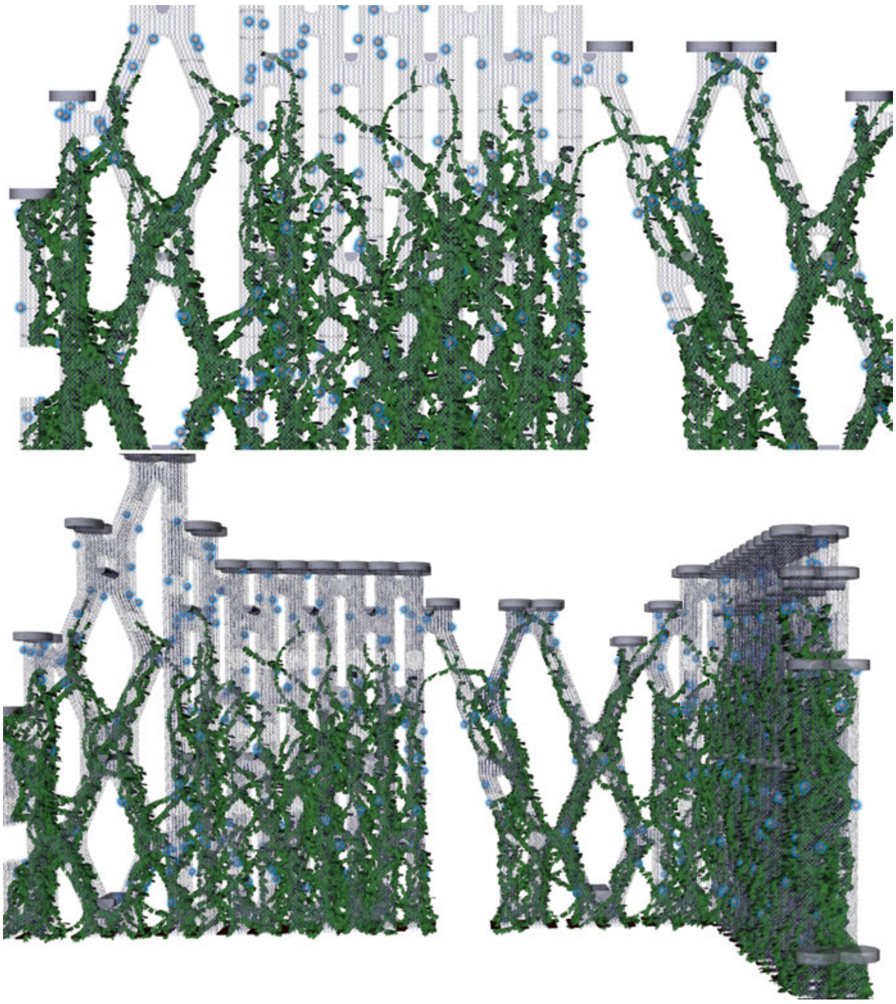


Figure 92: Some views of the resulting example growth. (Top) Side view, (bottom) perspective view, including a view through into one of the walls, on the righthand side.

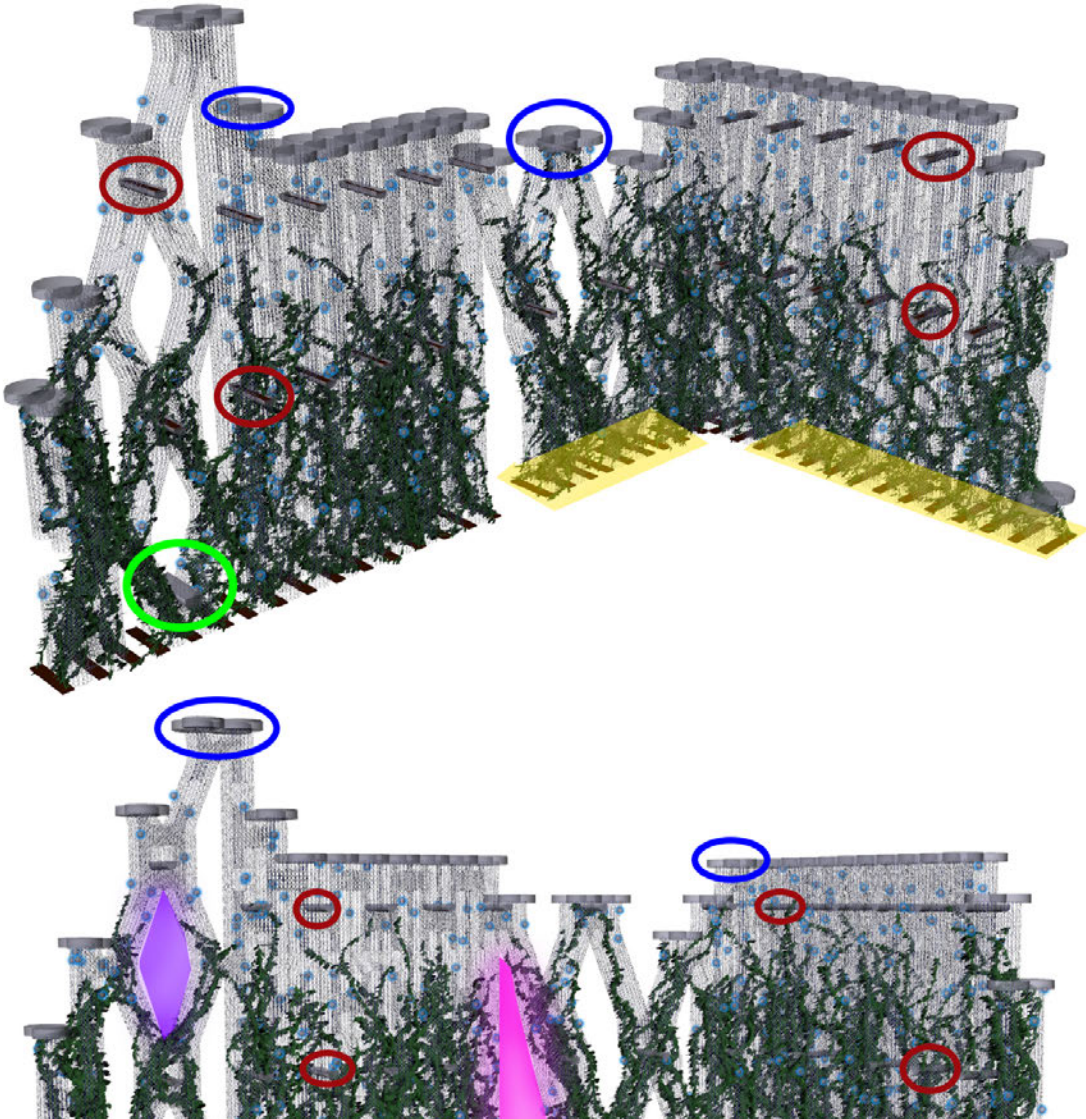


Figure 93: An overview of the example growth, with key features highlighted. Green circle: seat embedded in the wall; pink highlight: doorway; purple highlight: window; yellow highlight: soil beds on the ground plane; red circle: soil beds incorporated in the braided scaffold, situated at upper points on the braid; blue circle: portions of the braid machine.

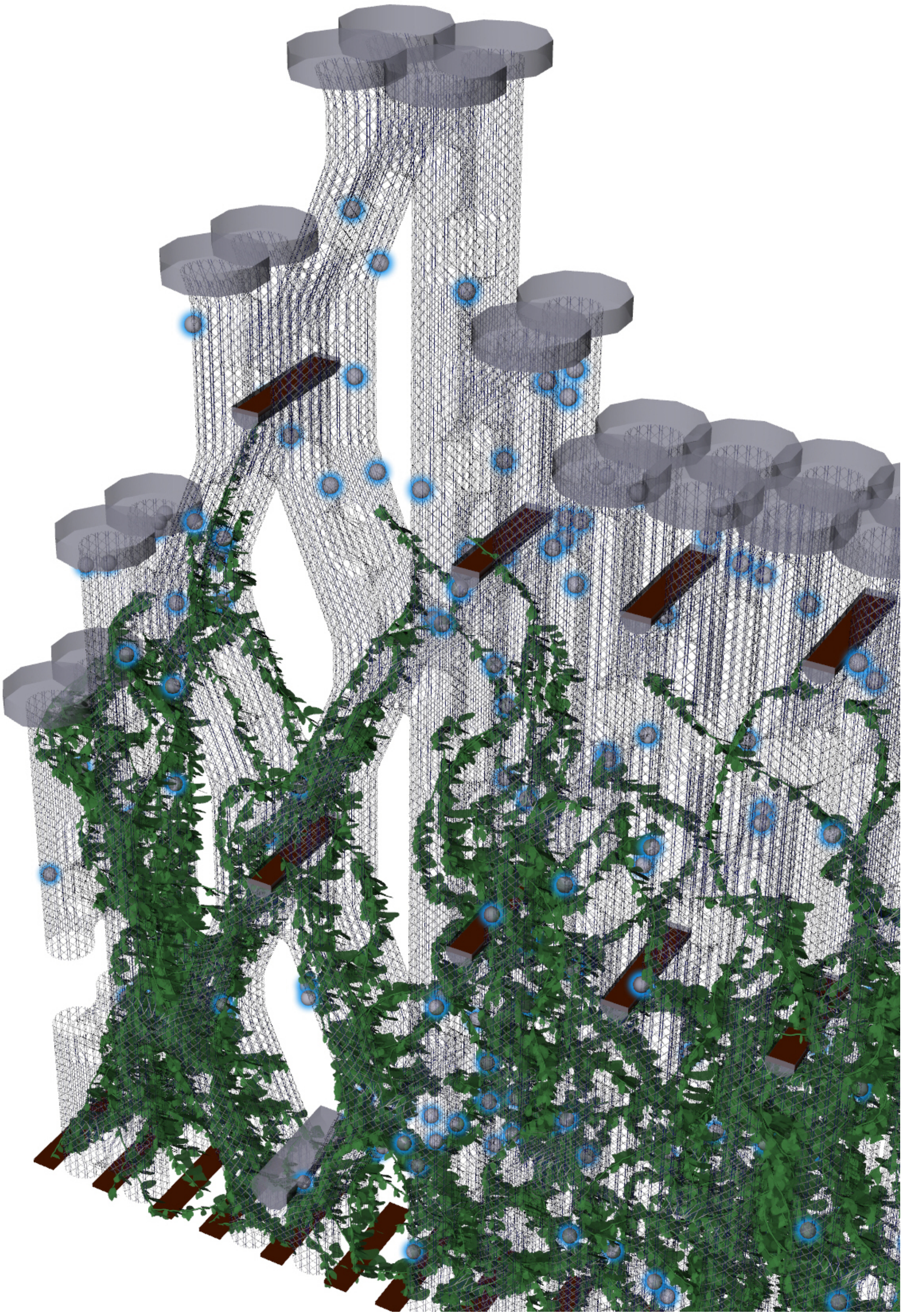


Figure 94: A detail view of the example growth, where many incorporated components can be clearly seen.

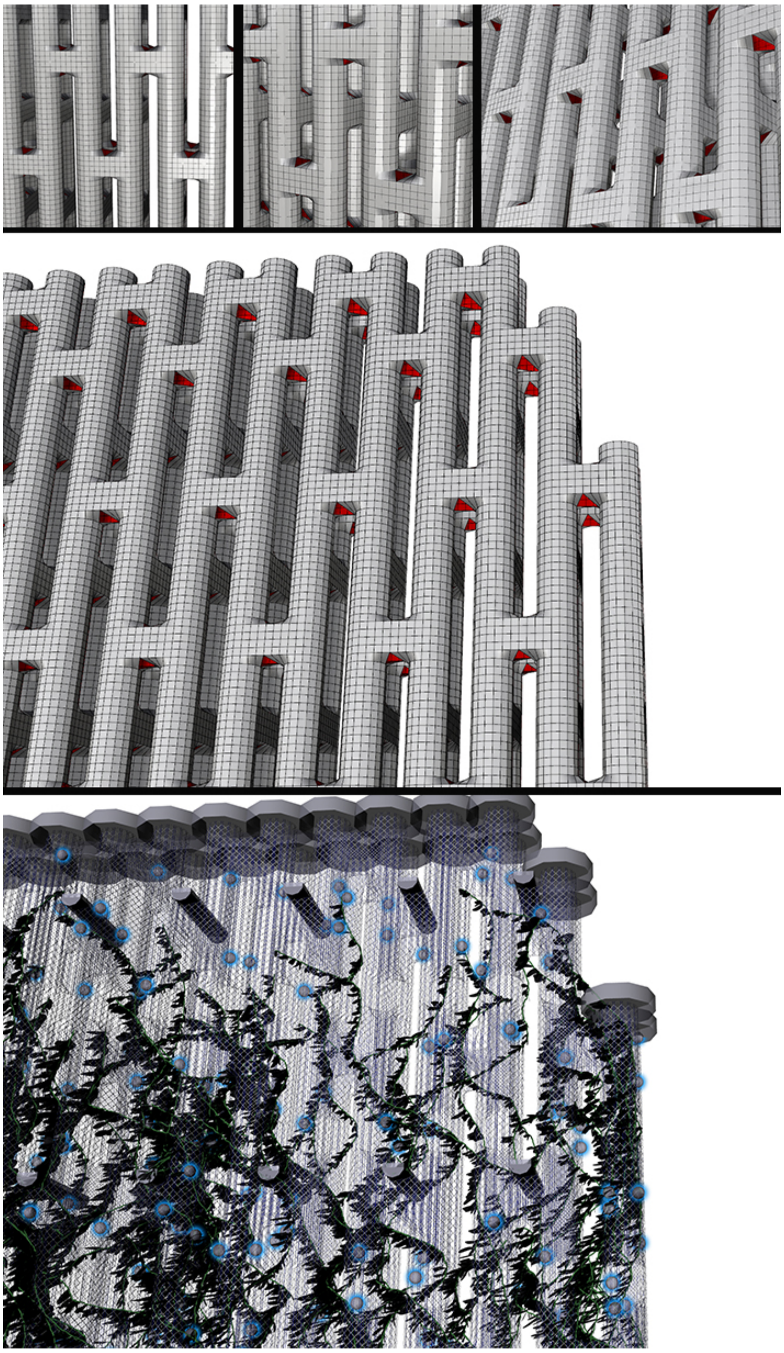


Figure 95: A visual to help illustrate the pattern of rotating and alternating bifurcations and mergers present in the braid of the example growth, which forms a thick construction suitable to host various components expected in an external wall system.

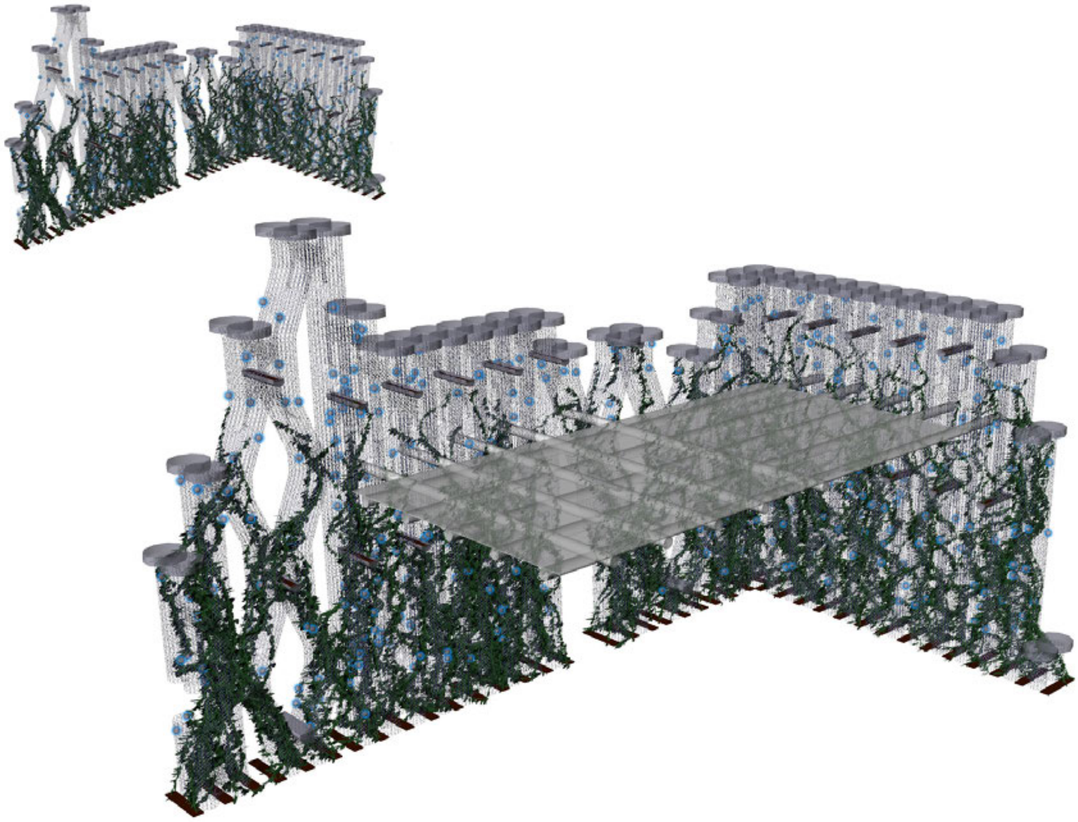


Figure 96: The speculative mounting of mechanical elements to incorporate a second-story floor-plate in the example growth.

3.3.3. Impact of human judgment: Architectural use propositions

Self-organizing construction is an emerging subdomain for on-site construction robots. This not only presents new challenges for robotics, but due to the stochasticity involved in such systems, impacts the modeling and prediction of resulting built structures in the process of architectural design. Self-organizing models have been explored by architects for generative design and for optimization, but so far have infrequently been studied in the context of construction. Under current development, we devise a strategy for architects to design with non-deterministic self-organizing behaviors, using interactive evolution to incorporate designer judgment informed by domain-specific knowledge. We use the IGP method, having implemented it into a software pipeline for early phase design for architects. In current developments, we test the software with an initial user group of architects, to see whether the method and pipeline helps them design a non-deterministic self-organizing behavior. This work will be detailed in future reporting.

3.3.4. Looking ahead to the Social Garden

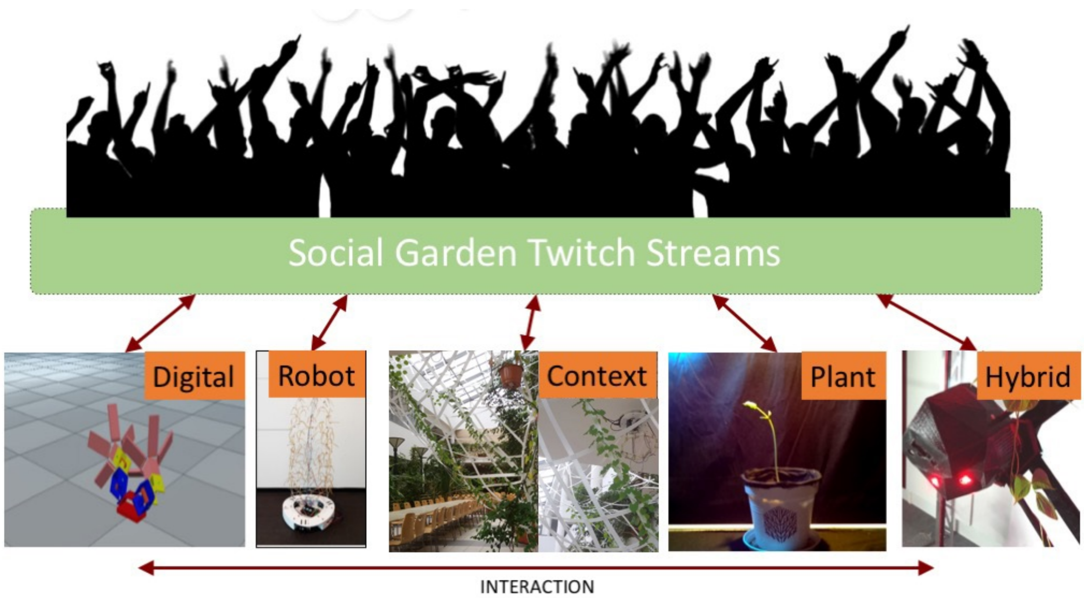


Figure 97: The developed twitch setup for the Social Garden.

The ultimate goal of *flora robotica* is the creation and exploration of a plant-robot-human ecology in the form of an architectural ensemble. This can be a single entity in the form of an inhibited living architecture or it can be a collection of spatially distributed *flora robotica* systems a technologically enhanced Social Garden, which is under development and will be reported in future deliverable D3.3. In our project, the Social Garden will be explored in physical and digital instances. The physical presence will incorporate all sites of physical *flora robotica* and connect these over the Internet. The digital component of the Social Garden is Internet-based, allows for virtual user interaction, and acts as a searchable data repository of growth patterns, control algorithms, and data tested and acquired at the physical sites.

The idea of the digital presence of *flora robotica* is to connect all our approaches (simulation and plant/robot experiments) and to make our developments available to a wider community.

Users can experience the Social Garden remotely, they are attracted to the idea of living architecture, they are allowed to interact with the robots directly, and may share growth patterns and plant growing recipes. A possible technology to implement an interaction interface is Twitch.

All communication in Twitch is done in the chat interface and this interface can be directly extracted using a chat bot that we have developed. Our chat-bot is an implementation of a python-based interface originally developed by [3]. We can directly extract any message that has been posted in the twitch channels along with the associated user name. In an initial implementation a Twitch user controlled a modular robot with a varying amount of modules. The user was also allowed to request changes of the robots morphology.

There are some planned uses and priorities for the Social Garden which the Twitch setup might not encompass, so there is also a central database planned for the Social Garden, to host all relevant models and data streams of the project. This planned central database will be used to, among other things, source model and data inputs for simulated projections in the IGP setup.

4 Growing Building Components

4.1 Defining functions and types for grown building components

Next to the envisioning and projection of grown spaces, we investigate the functional and categorical types of building components able to be constructed via the *flora robotica* system.

4.1.1. Grown components in the literature: Artisan, indigenous & research

Though there is not, to our knowledge, any work outside of *flora robotica* on the topic of **autonomously** shaping plant growth, through either roboticly provided stimuli or otherwise, various groups and individuals have **manually** shaped plant growth via mechanical constraint or enforcement. This type of work, to our knowledge, has not been comprehensively collected into a group and analyzed as a category. Therefore, we conduct a review of this body of work, to catalog and to form a research perspective on mechanical and structural roles that are able to be performed by shaped plant growth. Building our perspective on this review of existing work is especially productive for *flora robotica* because of the substantial overhead associated with plant experiments, limiting the feasible length of our experiments in the project, as well as the feasible quantity both of experiment types and of repetitions.

Figure 98: Production process of Munro and Full Grown [95], strapping young trees reusable industrial molds [121]. Image from www.dailymail.co.uk/news/article-3033546.

The literature regarding the manual shaping of plant growth into artifacts and structures is fragmented over a wide variety of arts, humanities, commercial, and engineering disciplines, including artistic production, commercial product production (see Fig. 98), historical study of geographic communities, architectural design research, and structural engineering studies of indigenously built structures (see Fig. 99). We therefore look not only at scientific publications, but also at so-called 'gray literature' [144].

Figure 99: *Living Root Bridges* indigenously constructed in Meghalaya, India. Image from WikiCommons Media user Arshiya Urveeja Bose, licensed as CC-A 2.0.

Figure 100: Building façades designed by Patrick Blanc [32].

Scaffolds hosting plants or habitats Basic mechanical scaffolds on building façades and roofs have been used extensively in building construction to host plants as green walls and green roofs [69, 50]. This strategy is exemplified in façades designed by Patrick Blanc, as described by Gandy [32] (see Fig. 100). The plants, and especially the soil mass required to host the plants, serve a substantial thermal insulation role and may also work to mitigate the urban heat island effect [128] and manage urban stormwater [127]. Examples in the literature work to advance the flexibility or functionality of the common green walls approach. While typical green walls are hosted in standardized and inflexible engineered building systems, [129] investigate 3-d printed solutions for suitable growth substrates, achieving flexibility in geometry and in fabrication process. Another approach to increased flexibility is taken in the *Plug-In Ecology* project by Joachim [57], where plants are individually hosted in modular building components that can discretely pop in and out of a larger structure. Besides flexibility, the functionality of plants on mechanical scaffolds is increased in the *Eco Boulevard in Vallecas*, by Ecosistema Urbano et al. [24][2], and in the *Baubotanik Nagold Tree Hub* and *Baubotanical Tower*, by [79, 80], in all of which trees are planted upon an open structural frame and are grown to fill in gaps and form the façade of the building, rather than be added to an existing fully enclosed façade. Extending to further functionality, the [91] *RiverFIRST* project (see Fig. 101) supports a range of plants and animals present naturally in local habitats, with the aim of increasing biodiversity [cf. urban biodiversity, 37]. The systems described above and similar typically incorporate some robotic elements for automated irrigation, monitoring, and maintaining health of the plants. However, none of the aforementioned examples, or similar green walls we found in the literature, use their robotic elements to steer the location or shape of growth.

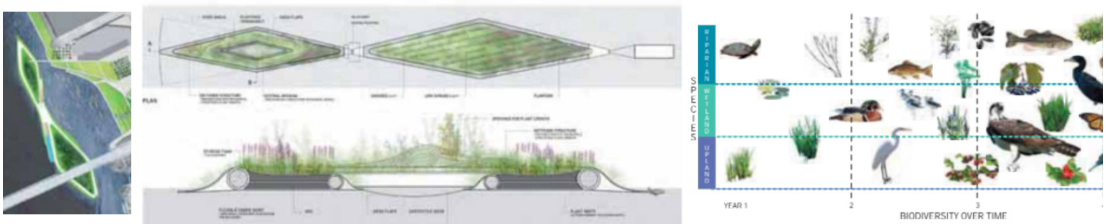


Figure 101: The *RiverFIRST* project [91] supports a range of plants and animals to increase biodiversity [cf. urban biodiversity, 37]. Biodiversity impacts in the ecosystem is validated; habitat currently under construction.

Guiding plant growth into load-bearing elements Many plant species are self-structuring, and their property of providing material with low resource cost can easily be seen as advantageous for building construction. However, it is less automatically clear that plants can fulfill structural roles for occupant loads and multi-story buildings. Existing examples of guiding or constraining plant stems into structures mostly have been made by artistic handcraft practitioners or through indigenous traditions, partly because grown structures that are substantially large at present must have been begun years or decades ago. These approaches include manually rearranging roots, braiding or weaving stems, constraining stems into bundles, joining stems through grafting, and constraining stems onto temporary molds. As a whole, these examples give evidence for

[2]This citation, like several others here, may look odd for citing a company as an author. Due to the interdisciplinary scope of this survey, we take also an interdisciplinary approach to citing work. Buildings, like paintings or sculptures, are citable works of intellectual property; example of how to cite artworks refer to Gibaldi [35]; addition of buildings as of 1990 refer to Winick [148]. If the team of architects or artists has not written a scientific paper about their structure, then it is necessary for us to cite the third-party author who has published a description and photograph(s) of the original work, from which we were able to understand the structure. In this case, the citation style we have chosen is such that the in-text citation (often including a company as an author) is for the original structure, and its respective bibliography entry in turn points to the third-party source publishing its image.

the ability of plants to perform certain structural or building envelope roles. Newer studies in scientific or engineering fields extend these handcraft approaches, for example by embedding permanent mechanical elements into natural growth to perform supplementary roles (e.g., floor plates, handrails).

Manually guiding growth in the Living Root Bridges Several examples of building sized structures, functioning successfully for occupant loads, can be seen in the so-called *Living Root Bridges* constructed in Meghalaya, India (see Fig. 99). As described by Shankar [124] and by Chaudhuri et al. [16], these bridges, made from live plants over a period of years or decades, are demonstrated to structurally outlast steel suspension bridges in the area due to high levels of moisture and dynamic loads such as flash floods. According to Shankar [124], the *Living Root Bridges*, once constructed, can last for centuries with minimal maintenance, and are even used in the area to replace failing cable bridges. Shankar [124] document the following process of light manual guidance of natural growth by which the bridges are formed over a period of 15 to 30 years: first, a hollowed tree trunk supported by bamboo scaffolding is used to guide young, pliable *Ficus elastica* roots across a desired bridge location, sometimes from both sides; second, multiple layers of ficus roots are guided through the trunk until the combined roots are self-supporting and the trunk is removed; third, multiple layers of roots are guided along the bamboo scaffold, until they too are self-structuring and the bamboo is gradually removed; finally (or simultaneously with the previous step), 'dead load' such as stones, wood planks, and dirt are added to fill gaps and to test the bridge for structural stability (see Fig. 102(a)). According to Shankar [124], mature bridges can carry loads of up to 35 people. In some cases, when existing cable bridges fail, they are repaired by twining these same plants within the cables, until the plant growth matures enough to perform structurally [124] (see Fig. 102(b)).

Mechanically constraining growth While in their young, pliable state, plant stems can be manually placed in a desired position, and then mechanically constrained in that position. This can be completed with pliable woody species such as willows, though the stems do not have substantial structural properties individually, by permanently constraining the stems in tightly braided patterns (often termed "woven" by gardeners and other practitioners, see Fig. 103(a), left) or in large, strong bundles (termed 'poling,' see Fig. 103(a), right). Over time, the individual plants sometimes naturally graft with their constrained neighbors, but we are not aware of any examples where natural grafting is demonstrated to give additional load-bearing capacity to bundled stems. Willows are especially common for practitioners to use, because live plants can be cut and then used to build with, and then once in the desired positions, the cut ends can be 're-planted,' where they will sprout new roots and continue to grow normally [29]. Examples of living willow construction are partially surveyed by Ludwig [76] and more generally surveyed by Gale [29] in their respective literature reviews. Gale [29] note that the construction methods used for these living structures are based on ancient Sumerian techniques for building with cut reeds, currently still used in Iraq. Though these reed structures use dried plants rather than live plants, their methods of bending and constraining can be extended to live willows. Some of the simpler reed structures, described by Mandilawi [82], closely resemble many of the living willow structures. However, a significant category of reed structures – the so-called *mudhifs* – are vastly more architecturally sophisticated, able to serve standard building functions for long-term occupancy. New *mudhifs*, according to Broadbent [14], are currently underway that include water and electricity utilities, allowing functions such as cooling, refrigeration, and Internet connection. Though the *mudhifs*, historically documented by Broadbent [14] and architecturally analyzed by Mandilawi [82], are made from cut and dried reeds, their construction techniques could be investigated for buildings made from living plants.

(a) Adding mechanical elements like stepping stones to a living root bridge that has reached a maturity stage of being able to support live loads. [124]

(b) Living roots used to repair a failing cable bridge. [124]

Figure 102: *Living Root Bridges* of Meghalaya, India [124].

In the existing living willow structures, the braided or bundled stems form a structural frame, but not a fully enclosed interior. Two methods are documented in the literature for adding a

(a) Methods of braiding or weaving, and bundling in order to increase the structural performance of pliable willows. (Left) [29], (right) [62] described by [29]

(b) (Left) *Living Willow Tunnel* by [29], (right)*Hopland Willow Dome* by [119] described by [29]

Figure 103: Methods for constructing with living willows, and their respective results [29].

façade or canopy to shelter occupants from wind or rain. One method, for tightly braided living willows, is to allow the foliage that grows from the stems to cover the small gaps in the braided structure, as seen in the *Living Willow Tunnel* by Gale [30] (see Fig. 103(b), left). This does not provide a full enclosure, but can effectively buffer wind or rain if growth is allowed to mature for several weeks. The method can also be used for bundled structures, despite the much larger gaps, by following a longer construction process as seen in the *Hopland Willow Dome* by Schaeffer et al. [119] (see Fig. 103(b), right). In this application, as the willows in the bundled structure mature and grow branches, the new shoots are periodically constrained in locations where denser cover is desired, until the branches are thick enough that their foliage can buffer rainfall. A thick canopy was achieved in the *Hopland Willow Dome* within six years of growth, as documented by Calkins [15]. The second method is to use the living willows as structure only, and to use typical building materials to shade and shelter the structure's interior, as seen in the tensioned textile roof of the *Rostock Willow Church* by Kalberer and Sanfte Strukturen [62][3] (see Fig. 104). In the

[3]see footnote 2

Figure 104: The *Rostock Willow Church*, a *Sanfte Strukturen* living willow structure by Kalberer and Sanfte Strukturen [62]; image from Wiki Commons, license CC BY 2.5 [1].

built examples using these two methods, their respective canopies provide some degree of shelter, but they are far from full enclosure for long-term occupancy. By contrast, the *mudhifs* described above include fully functioning façades and roofs, with architectural details like columns, vaults, windows and doors [see 82, 14]. The finished *mudhifs* use exclusively constrained reeds to form these architectural details, as the structures can be untied and reassembled on other sites, according to Broadbent [14]. These *mudhif* construction techniques, so far used only for dried reeds, could be investigated to extend living willow structural frames into fully enclosed living willow buildings for long-term occupation, depending on the whether the plants can be kept healthy in such a dense structure.

Weaving, braiding and constraining willow is popular for handcraft of living sculpture, furniture, and small architectural elements such as fences or garden tunnels [19, 142, 29]. Larger structures that exist in the literature are constructed by bundling willow rather than braiding or weaving it, and have been constructed from 1985 onward by Marcel Kalberer and *Sanfte Strukturen*, as described by [59, 60]. There are many examples of these *Sanfte Strukturen* bundled living willow structures that are of multi-story height. These examples mostly have only single-story occupancy however, so they do not test the ability of these structures to support live occupancy loads. There is one *Sanfte Strukturen* structure we know of that includes some multi-story occupancy, by having a second-story loft accessible by stair. However, the larger of *Sanfte Strukturen* structures sometimes include metal poles for structural reinforcement, according to [29], and there is no documentation available indicating whether this is the case for structure containing the second-story loft. The *Auerstedt Auerworld Palast* by Kalberer and Sanfte Strukturen [61], constructed in 1998 has successfully reached mature growth according to the architect's original design, and continues to live healthily as of its documentation by Gale

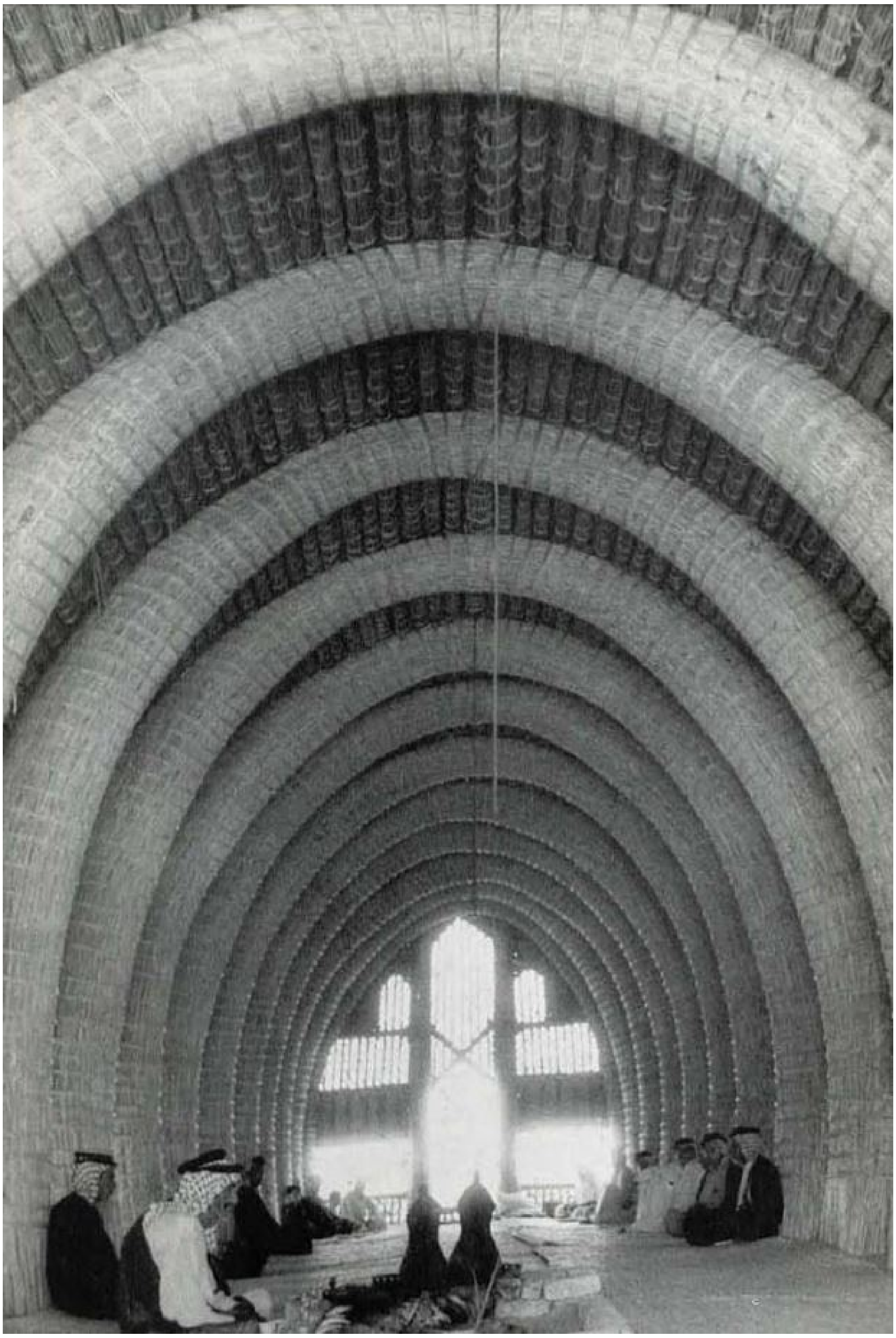


Figure 105: Image by Thesiger [133], republished by Mandilawi [82].

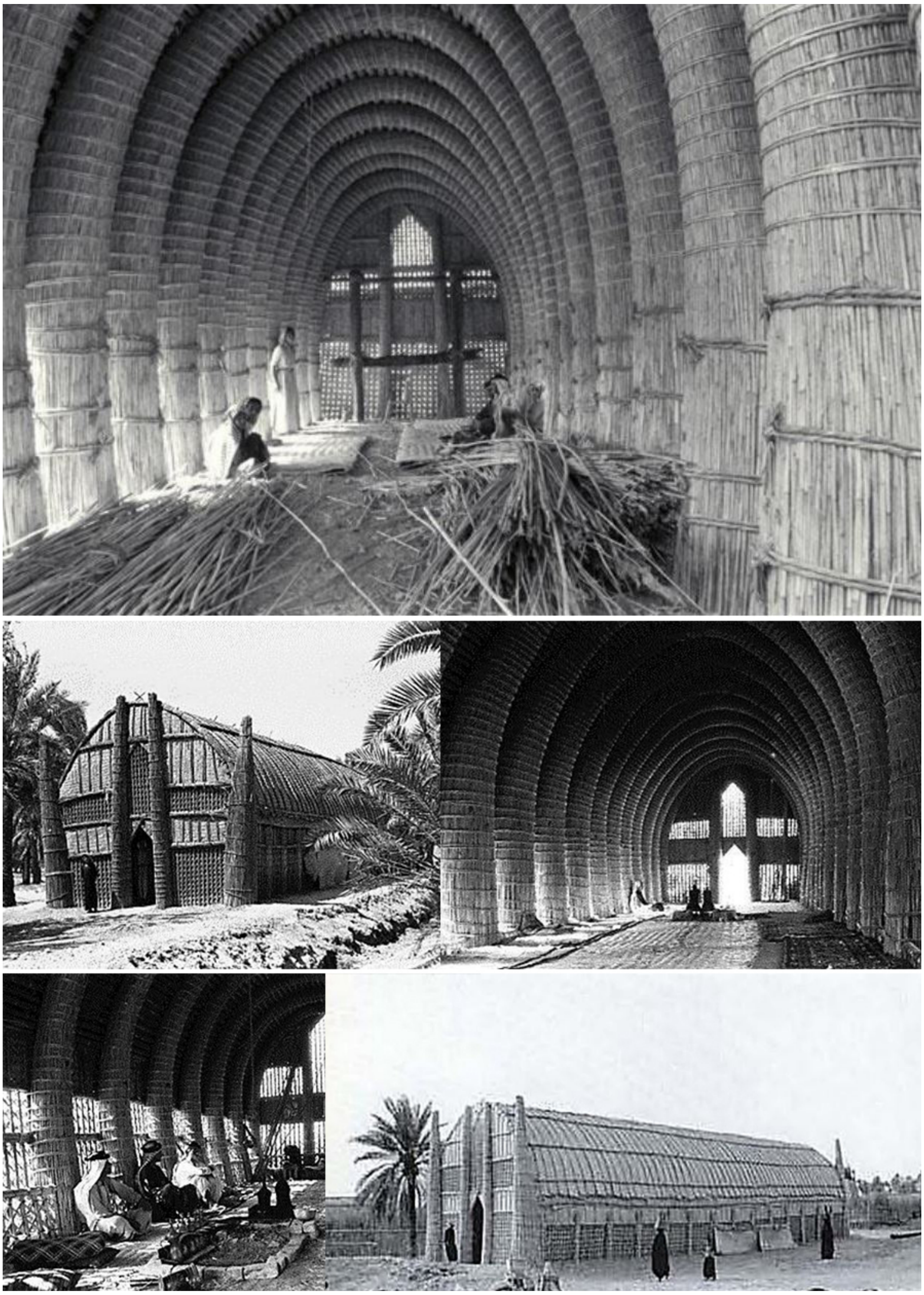


Figure 106: Images by Thesiger [133], republished by Mandilawi [82]

[29]. The most utilized of these structures has arguably been the *Rostock Willow Church* by [62] described above for its textile roof, part of the *World Horticultural Exposition* in Rostock, Germany. Here, we have gathered images of some *Sanfte Strukturen* example structures built during the last 15 years, from the *Sanfte Strukturen* website[4].

Figure 107: An example *Sanfte Strukturen* living willow structure, built in 2005. *Sanfte Strukturen* structures have been shown to remain reliable and in good condition over time, according to Gale [29]. This structure is shown in use by the public. Image from *Sanfte Strukturen* website: http://www.sanftestrukturen.de/.

Joining constrained growths via grafting Alternatively to willow, plants that become woody and very structurally stiff in late growth phases can be constrained while they are young, until the plant has matured enough that constraints are no longer needed to keep the plant in position. This strategy can be used with plants that have substantially more structural potential than willow, but of course these species also have a longer growth period to reach maturity. This method typically incorporates natural grafting, and is often additionally extended to include hand grafting during the process of mechanical constraint. After hand grafting, constraints apply so much pressure that stems are joined together through natural growth processes over time. Examples of such structures have been surveyed in part by Ludwig [76], [29], and [64] in their respective literature reviews. When used to construct sculpture, furniture, and other smaller elements, this strategy is often termed *arborsculpture* or *tree shaping*, and has been used

[4] http://www.sanftestrukturen.de/

Figure 108: An example *Sanfte Strukturen* living willow structure, built in 2012. Described by Gale [29]; image from *Sanfte Strukturen* website: http://www.sanftestrukturen.de/.

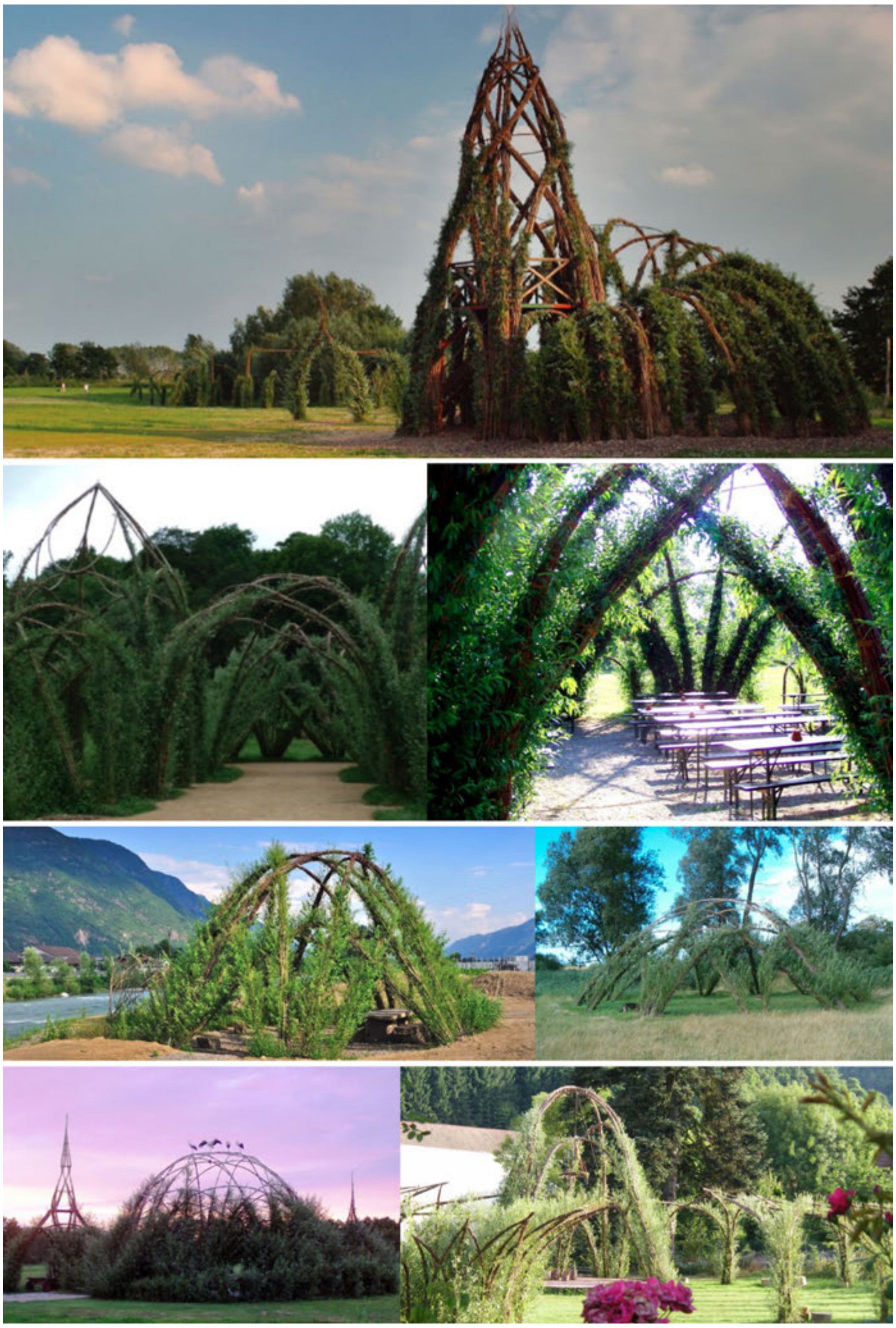


Figure 109: Some *Sanfte Strukturen* example living willow structures. (Top image) Structure from 2005, including a 2nd-story loft in the "tower" portion, accessible by stair. (Other images) various structures from last 15 years, at various stages of growth. Images from *Sanfte Strukturen* website: http://www.sanftestrukturen.de/.

to make a wide variety of growths [109, 110, 26, 66, 29, 76, 64]. Besides trunks or stems, it is also possible to keep partial root systems above ground and shape them, as described for ficus trees by Golan [38].

Figure 110: *Gilroy Gardens Basket Tree* by Axel Erlandson [25], constructed c. 1940s. Images by Reames [109], republished in [76]. (Left) Condition in 1967, where upon careful inspection, the original biaxial braid organization of the stems is still discernible; (right) condition in 2004, where the individual trees have fused heavily, forming a fairly continuous diagrid structure.

Several large sized grafted tree sculptures were constructed by Axel Erlandson decades ago [26], and have thus had time to mature. His c. 1940s *Gilroy Gardens Basket Tree* [25], which is comprised of several trees braided together to form a hollow diagrid-surface column, provides evidence that mature shaped and grafted trees could have structural success at multi-story heights.

Many grafted living structures meant to function as buildings or architectural elements have been begun by Kirsch [66], who according to Gale [29] and Ludwig [76] has based his process on the historic patents of [146, 147]. Though not yet mature, the *Kassel Waldgartendorf* by Kirsch and Block [68] is showing success in its middle growth phases, as documented by Ludwig [76]. The existing living tree structure that is designed to be functionally closest to an occupied building is the *Ash Dome* by Kirsch [67], planned to have a fully enclosed living roof, fully enclosed living walls with windows, and several subdivided rooms [66]. The *Ash Dome* is still in middle growth phases, but is growing successfully and has had preparations for electrical utilities added, as of its documentation by Gale [29]. Its design is comprised of tightly braided trees with very small

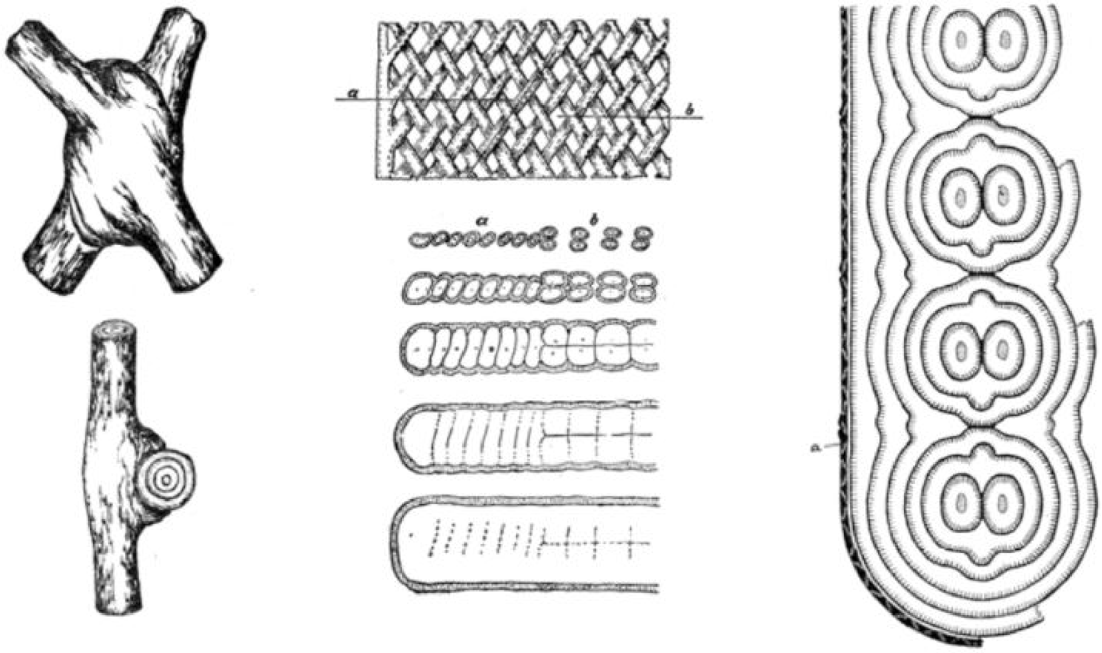


Figure 111: Wiechula's 1920s patent illustrations showing how his manually woven (or braided) woody stems would naturally graft together overtime through the pressure of their intertwined organization, in theory eventually forming a completely solid living-wood wall. This stage of growth—grafting into a completely solid wall—has so far not been demonstrated in any of growths constructed by practitioners in this section, to our knowledge. Growths will take many decades to reach that point, and so far none of the growths, to our knowledge, has reached a mature enough stage to test weather the stems will in fact fuse completely if given sufficient growth time. Images are from the historic patents of Wiechula [146, 147], republished in [76].

gaps between them, meant to eventually graft together into solid continuous walls. The later growth phases of this structure will test whether its solid living wall strategy can be successful and can maintain plant health. A very recently planted structure, *The Patient Gardener* by Visiondivision and Politecnico di Milano [139][5], plans to apply the *arborsculpture* approach to construct a two-story building structurally fit for occupancy. Its design uses living trees as both wall supports and floor supports by planning to bend and join the trees through grafting at mid-height, forming an overall hourglass shape for the structure. Its growth phases are still too early to provide evidence for whether its strategy of acute bending will provide sufficient joint pressure for successful grafting, a primary concern among *arborsculpturists* according to Gale [29].

Combining constrained growth with mechanical scaffolds In contrast to the fully living structures described above, the literature also includes hybrid approaches, in which constrained living plants are combined with mechanical scaffolds. Two strategies for these hybrid approaches are documented in the literature, one which uses the mechanical scaffold as a temporary mold, and one which embeds the mechanical scaffold into plant tissue and incorporates it permanently

[5]see footnote 2

(a) The *Ash Dome* by [67], documented by [29]

(b) The *Kassel Waldgartendorf* by [68], images from [76]. (Left) Structure planted in 1997, photograph from 2008; (center,right) structure planted in 1993, photograph from 2008.

Figure 112: Structures built from living willows that have been tightly braided together.

as part of the structure.

For the method of using mechanical scaffolds as removable molds, the examples in the literature are the size of furniture or architectural elements, and plan for the grown object to be harvested at a certain stage, for processing into industrial products. Before the stage of har-

(a) The idea of taking an agricultural approach to mass-producing furniture, by constraining the plants to molds or jigs, has been around since at least the 1980s when Chris Cattle envisioned a "furniture orchard," as quoted in [58]. Image reprinted from [58]

(b) Using shaped tubes to direct growth [10] or other similar setups of reconfigurable molds, as an alternative to static jigs, is a mechanical approach to shaping plant growth that has the potential to be automated. Image reprinted from [10].

(c) The *Baubotanik Footbridge* by Ludwig et al. [78]. (Left) As constructed, in Spring 2005, (center) condition in Summer 2005, (right) condition in Summer 2010. Saplings are held in place around the mechanical elements using industrial fibre-reinforced strapping (see red circle, left), which remain in place throughout growth (see red circle, right). Images reprinted from [76]; red circles added.

Figure 113: Three different methods of shaping plants by constraining them to or with mechanical elements.

vesting, Richardson et al. [112] strap bamboo onto mechanical profile formers during growth, constraining them in the shape of a vehicle frame. This example is not yet extended to the processing stage after growth. Finished furniture products such as stools, using young trees strapped to small molds during growth, have been made by Chris Cattle for decades, as described by Johnson [58]. Products such as chairs and lamps are made by Munro and Full Grown [95], using young trees strapped to reusable industrial molds in a process that nears mass manufacture [121]. An extension of the mold method is investigated by Beger et al. [10], using shaped tubes to direct growth, instead of constraining it fully. Though the existing uses of molds are for furniture-sized elements, and for products that are harvested rather than maintained indefinitely in a living state, similar molds could be investigated for larger and longer term growth, with molds applied incrementally or holistically.

(a) The *Baubotanik Footbridge* by [78]. Images reprinted from [76]

(b) The *Baubotanik Nagold Tree Hub* by [80]. Images reprinted from [76]

Figure 114: *Baubotanik* structures in which living trees are meant to grow to support mechanical structures.

The method of embedding mechanical scaffolds in plant tissue over time, and thereby creating a bio-hybrid structural system, has been investigated for the application of multi-story buildings. The *Baubotanik Footbridge* by Ludwig et al. [78] uses trees as living columns to support a steel platform and handrail at second-story height. The mechanical platform and handrails maintained their location and orientation throughout growth, because the trees were already taller than the height of the platform at the time of construction, according to Ludwig [77]. Though there were originally trees planted diagonally as well as vertically, the diagonals did not maintain health and did not survive early growth phases. The vertical trees were still healthy six years after construction, as documented by [77], and had by that time fully encircled the steel railings at their attachment points, embedding the railings into the living trunks. In order to extend these results to taller multi-story buildings, the *Baubotanik Nagold Tree Hub* and *Baubotanical Tower*, referred to above, were built by Ludwig et al. [79, 80]. In these two, free-standing steel structures were first built with columns and floor plates, with the intention to grow trees in a structural frame pattern around permanent floor plate perimeters at each level, until the trees mature enough that they can structurally support the floor plates and the temporary steel columns can be removed [77]. The growth on both of these structures is still too young to provide evidence for multi-level structural frames from living trees.

4.1.2. Structural

As we can see from the evidence in the literature, there are a number of key ways that grown building components incorporating living plants can perform structural roles. We define the following approaches as those able to be implemented and supported within the *flora robotica* system:

1. guiding plant growth along a scaffold, until the plants are self-structuring and the scaffold can be gradually removed;
2. using 'dead load' mechanical elements to fill gaps in a structure made from living plants, or otherwise incorporating useful mechanical elements whose function cannot easily be replaced by living plants;
3. repairing mechanical structures that have failed or been damaged, by growing twining plants in and around the structure, until the plant growth matures enough to perform structurally and functionally replace the failed mechanical elements;
4. tightly braiding plants together, such that the individual plants can naturally graft with their constrained neighbors over time, meant to eventually graft together into solid continuous walls;
5. using non-structural indivual plants to perform structurally in groups—*without* grafting—as long as sufficient twining has occurred;
6. using living plants for multi-story height and occupancy by using mature grafted trees, extremely twined plants loaded in tension, or by incorporating mechanical elements to form the floorplate of the second story; and
7. in order to build multi-story structures, building such that the soil and root systems of plants at upper stories are supported by the scaffold and plants of the lower stories, due to the limiting factors of the total growth height possible in most self-supporting plant species and the amount of additional time needed to grow plants (especially trees) to such extreme heights.

We propose below some strategies to achieving several of these within the *flora robotica* system, using the braid 3D modeling method and IGP method for plant growth in order to visualize them. We also propose some additional details based on the *flora robotica* use of braid.

First, we have seen in the literature that some species—at least willow— can be cut, then manipulated into a shape, positioned such that their cut ends are replanted in soil, and the cuttings will grow new root systems and continue their growth as normal. Therefore, we propose that cuttings of willow or a similar species could be autonomously braided using our braiding machine, then left to continue their growth. This strategy could potentially even be investigated for plants that should not be cut, by planting them in their final intended position, growing them to a meter or so in height, then braiding them by machine along with normal mechanical filaments, and leaving them to continue their normal climbing growth up the remaining braided scaffold (see Fig. 115). This could take advantage of strategy #4, listed above, eventually creating a very strong structural element in the portion where the plants have been braided.

Second, we have seen in the literature provisions made for the inclusion of electrical outlets, doorframes, handrails and other such elements in living plant structures. These provisions are made because the elements perform functions that are difficult to replicate using plant growth (see strategy #2, listed above). In our case, this particularity is true not only of plant growth, but in some cases also of braided structures. Therefore, we propose that, in order to incorporate

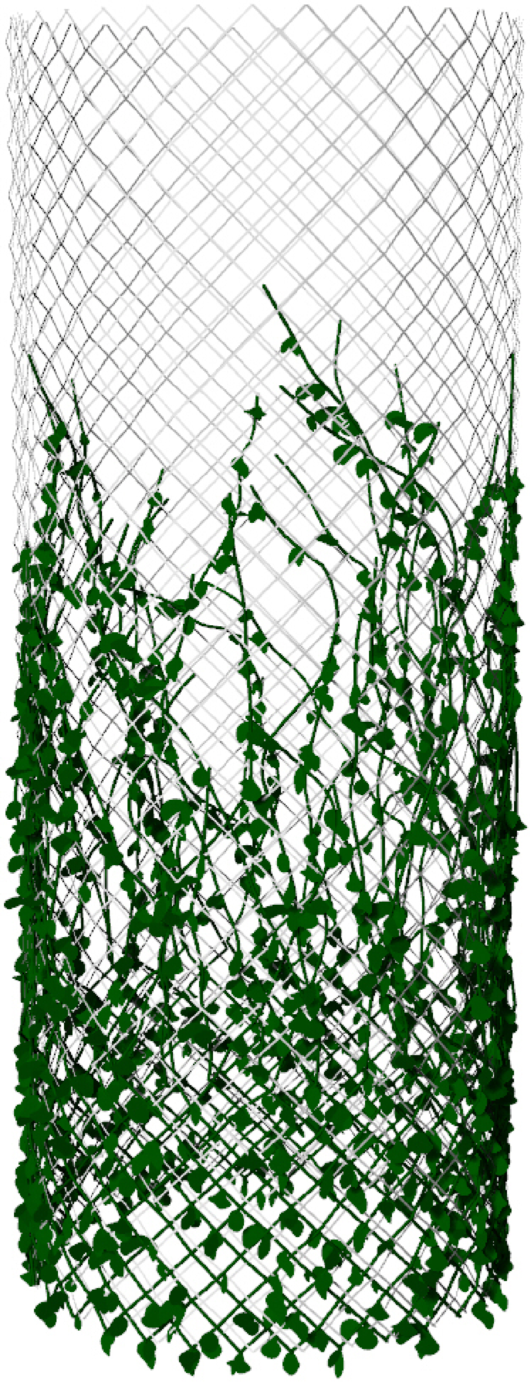


Figure 115: A tubular braid where plant stems have been braided in by machine at the bottom portion, then left to continue their normal growth up the scaffold.

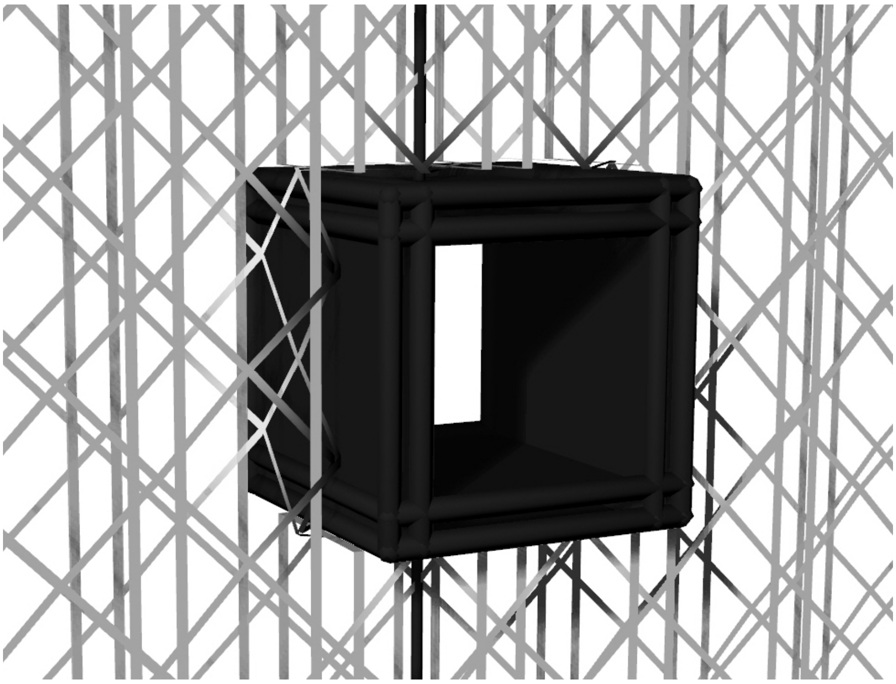
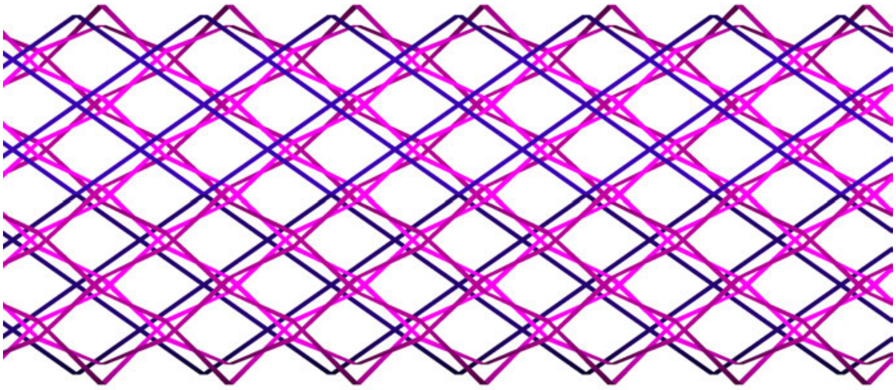


Figure 116: Functional elements such as utility infrastructure for long-term human occupation of buildings, is difficult to replace with either plants or braids. We therefore propose the incorporation of such elements directly into the braided scaffold, ideally as part of the machining process, before plants are grown there.

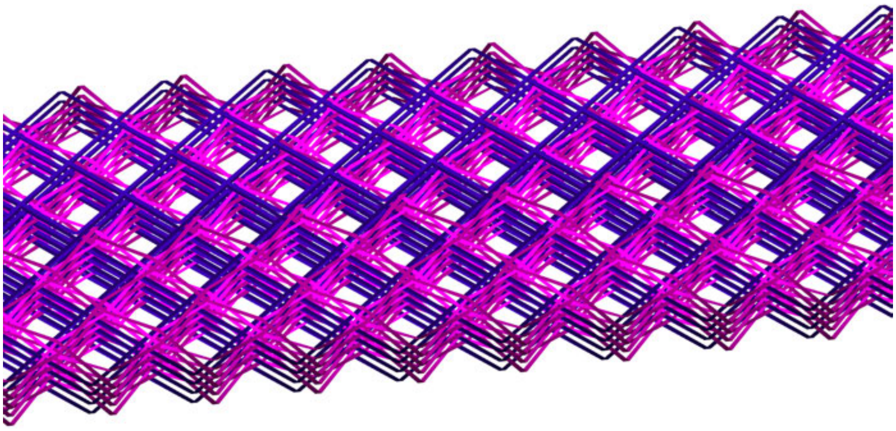
useful mechanical elements into our living plant structures, we first incorporate them into the braided scaffold where the plants will be steered (see example in Fig. 116). We extend this embedding of mechanical elements even further, described below.

Subset of 3D braids for flexibility in structural system: multilayer In order to expand the usefulness of the above strategy of embedding function-driven mechanical elements in the braid, we propose the use of a subset of the 3D braid category: specifically, multilayer (see Fig. 117). It has already been demonstrated that some types of 3D braids can be fabricated using the braid machine (see Sec. 2.4.1). Though this specific subset of 3D braids has not yet been demonstrated, in principle it is able to be fabricated by the braid machine, because it is more simple than the 3D braid already fabricated there. In this type of 3D braid, there are two more layers of normal 2D braid, but their meshes intersect, such that the individual braid surfaces interweave one another. This property of interweaving means that two 3D-interwoven braid surfaces can diverge for a period of rows (similar to bifurcation in tubular braids), and then merge again, forming new types of braid features that are useful for the embedding of mechanical elements.

Adding embedded compression elements to braid for hybrid structural systems A 2D tubular braid can be braided around a compression element. This strategy is frequently used in industry to create composite braided elements (see Fig. 118). A dense 2D braid sheet can be reorganized into a 3D braid comprised of two 2D braid sheets, between which mechanical



(a) Top view.



(b) Perspective view.

Figure 117: Example of 3D braid of the 'multilayer' type.

elements can be embedded. In this organization, the braid can be loaded in tension, while the embedded mechanical elements can be loaded in compression, thereby expanding the category of building components able to be constructed with braid that is made by the *flora robotica* braiding machine (see D1.2, D1.3). If mechanical elements such as lightweight beams are placed vertically in the centers of each ring in a chained figure-eight configuration of the braid machine (see D1.2, D1.3), this type of 3D braid with embedded elements can be completed. The result could be used as a reinforced wall, with the lightweight beams remaining vertical. Alternatively, that same result could be turned on its side, stretched such that the braid is loaded in tension, and—presuming the braid at each end is anchored sufficiently in some fashion—can in this way form a staircase (see Fig. 119). A staircase is an important building component to achieve, as it is crucial to any structure of multi-story occupancy, and thus far has not been able to be produced by any of out currently used braiding methods.

By extending this method, we can also propose the embedding of mechanical elements within a vertical braid wall, such that these mechanical elements can hold soil, root systems, and other resources, in order to grow plants directly at upper stories in multi-story structures (see Fig. 120). This approach allows the *flora robotica* system to support the potential for strategy #7 from the list above, significantly expanding the categories of structural types able to be encompassed. This is an important extension, as it would allow the *flora robotica* system to grow multi-story living structures at a fraction of the time previously considered to be necessary. In other words, in principle it would not take more time to grow a multi-story structure with multi-story occupancy than it would to grow a single-story structure with a functioning roof.

Figure 118: An industrial manufacturing process whereby a radial braid machine is used to braid around a preformed mechanical element. (Top) Before the braid has reached the mechanical element; (bottom) the braid formed around the mechanical element, such that the braid filaments are loaded in tension around the mechanical element, which is now loaded in compression. *Images sourced from* `www.tex-inter.ru`.

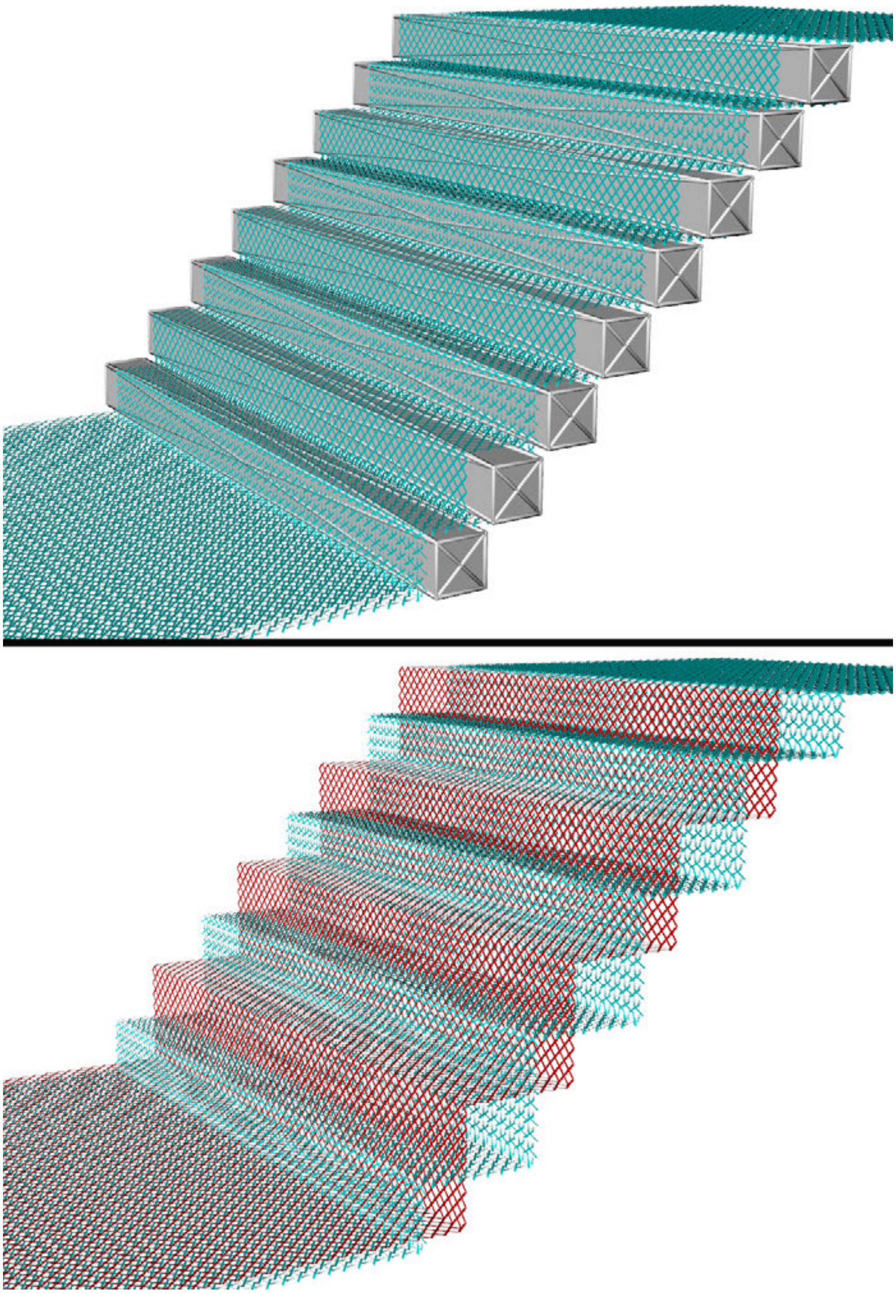


Figure 119: (Top) A multi-layer braid combined with embedded mechanical elements to form a stair. (Bottom) the two 2D layers of the 3D braid, with one layer visualized in blue and one in red. In this visualization, it is easy to see where the two layers are interwoven to form a 3D braid (braid sheets at the bottom and top of the stair), where they diverge (around each individual stair), and where they momentarily re-merge before diverging again (at each step transition, where each 2D braid switches its side of the stair).

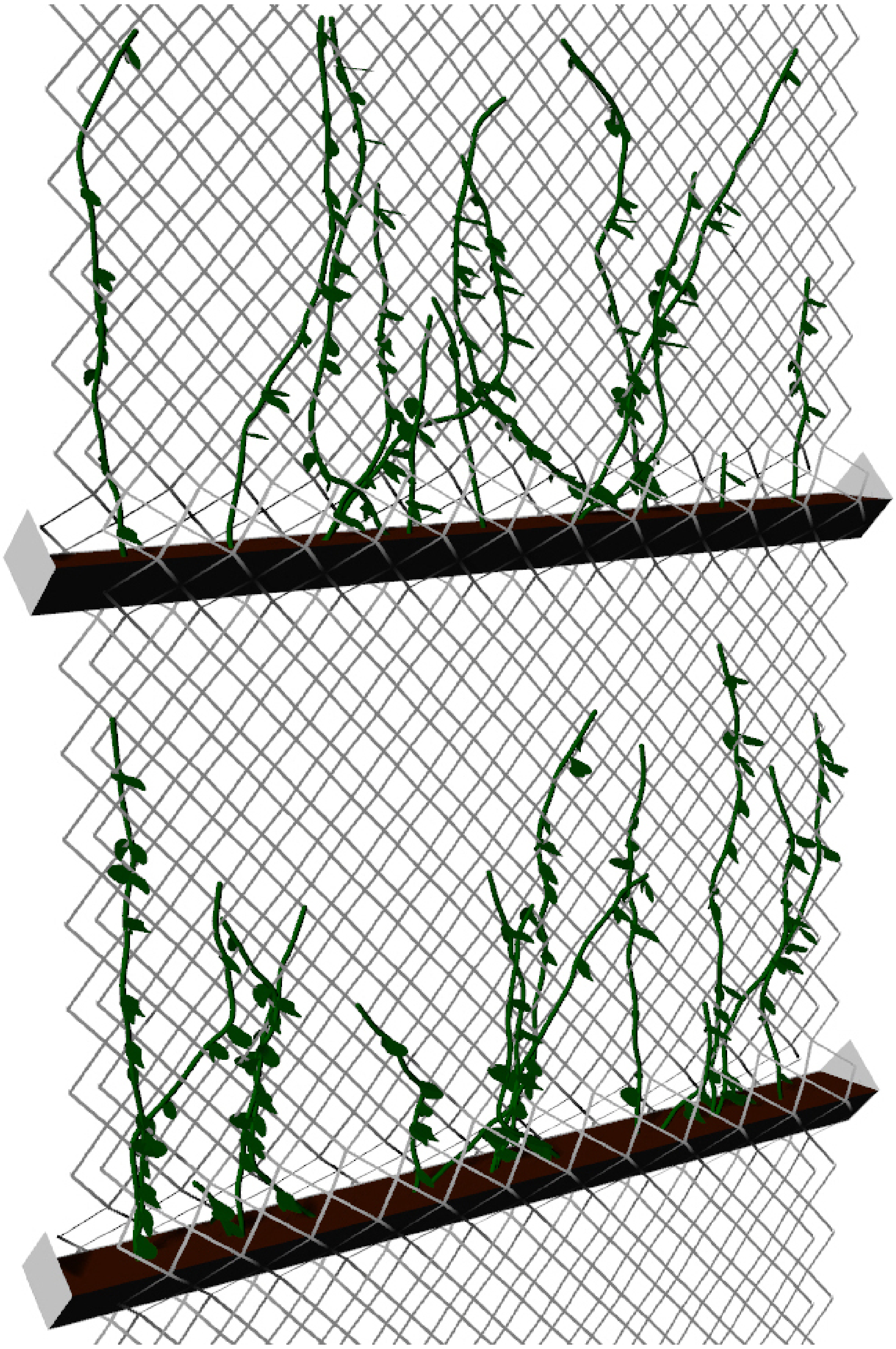


Figure 120: A 3D multilayer braid where the layers diverge to create pockets holding mechanical elements for soil and root systems.

4.1.3. Façade functions

Similarly to the structural elements, the literature gives evidence for several strategies of growing living structures that we consider to be applicable to the *flora robotica* system, in terms of constructing façade components that perform typical functions (e.g., wind buffering, solar shading, thermal insulation, etc). They are:

1. using plants' root systems, and especially the soil mass required to host the root systems, to serve as thermal insulation in a building façade;
2. growing plants on or in an open structural frame such as a braid, and allowing the growth to fill in gaps and form a solid façade barrier, even if the plants do not perform the structural role required to keep the system erect;
3. in a similar situation to the previous, using the partial enclosure provided by younger plant growth to buffer wind or rain, even if it does not provide an airtight moisture barrier;
4. following the same as the previous, but in a structure where the plants also form the structural elements using their stems, and can provide the added function of some façade feature using their leafy growth;
5. using plants as structural elements only, and augmenting with braid or mechanical elements of typical building material to shade and shelter the structure's interior, or perform other façade functions; and
6. using the pattern of gaps inherently present in braid, and likely to be present in early phase living façades, to provide sunlight exposure and cross-ventilation.

4.2 Mechanical performance

4.2.1. Braid incorporating embedded electronics

Electronic elements are incorporated in braided structures for a variety of purposes, such as sensing, actuating, power delivery, and communication. However, here we do not discuss any of these purposes (for descriptions of the various project hardware and its supporting software, see D1.3 and the rest of WP1). Rather, we discuss here the ways in which electronic elements can be mechanically integrated into braid, and the impacts those elements can have on the mechanical performance of braided building components.

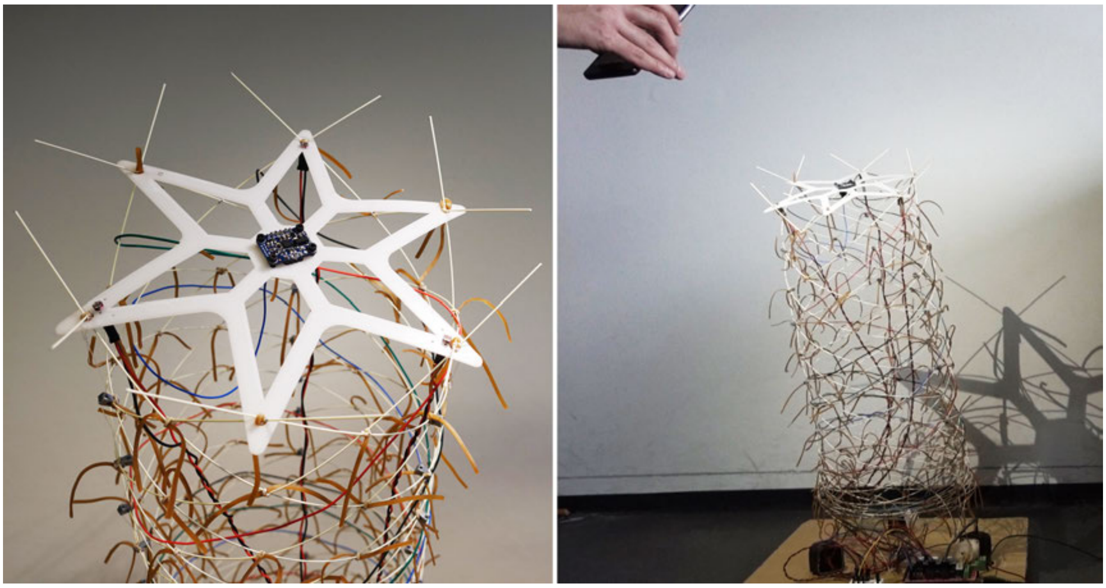


Figure 121: Electronics module as a stiff plate integrated at a tubular braid's cross-section, having a secondary mechanical role of increasing braid stiffness.

Compact modules One mechanical strategy to the integration of electronic elements is to compact them into a single localized module or group of modules. In this case, the modules will load the braid, applying a mechanical stress that needs to be supported. This strategy appears frequently in the project's hardware, such as in the plant shaping robotic nodes, phytosensing modules, and RaspiNet modules.

Though a compact module will always apply point-loads on the braided topology, thereby having the potential to enact significant deformation if the braid surface is not sufficiently stiff in the loaded direction, it can also be integrated into the braid in such a way that it performs a secondary mechanical role that supports the braid's overall stiffness.

In the star-plate shaped module hosting sensors on the 3 DOF braided manipulator (see D1.3, pictured in Fig. 121), the plate serves a secondary mechanical role by constricting the overall diameter of the braid tube at the location where is it attached. This has a similar effect as the elastic bands placed around the outside of a braid tube to stiffen it, in Sec. 2.2.3.

Alternatively, in the robot nodes for plant shaping (see D1.2 and Sec. 3.2.5), the nodes are conceived to explicitly serve a mechanical role, by attaching to the filament intersections in a braid (see Fig. 124), or the rod intersections in a diagrid (see Fig. 122 and 123). If the connection

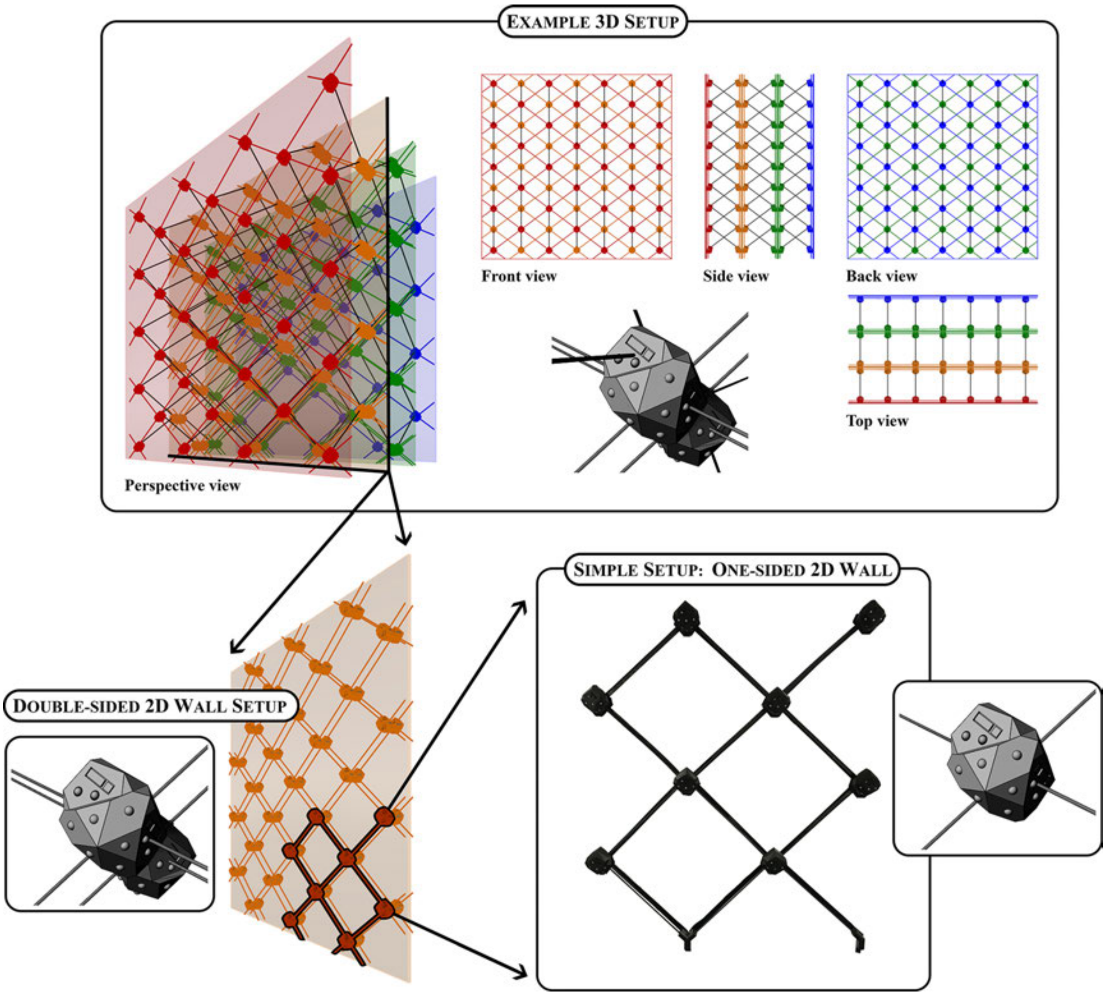


Figure 122: The robotic node is generalized to accommodate large scale 3D setups (image top). The experiments reported in this paper are reduced in dimensions (to 2D; image bottom) and scale (bottom right). They are used in experiments in a simple one-sided 2D wall setup (see experiments in D1.2 and D2.2), but are designed to be viable when scaling up to a larger group and adding a 3rd dimension. Each robot node has three possible scaffold attachment locations for an approaching plant, and three for a departing plant, with each location equipped with the respective sensors and LEDs for its function. In more extensive setups, two nodes can be affixed back-to-back to receive a combination of six scaffold attachments for approaching plants, and six for departing (bottom left). This back-to-back arrangement allows a flexible 3D setup (top), with a modular 3D diagrid scaffold that can be arranged in an extensive variety of configuration patterns.

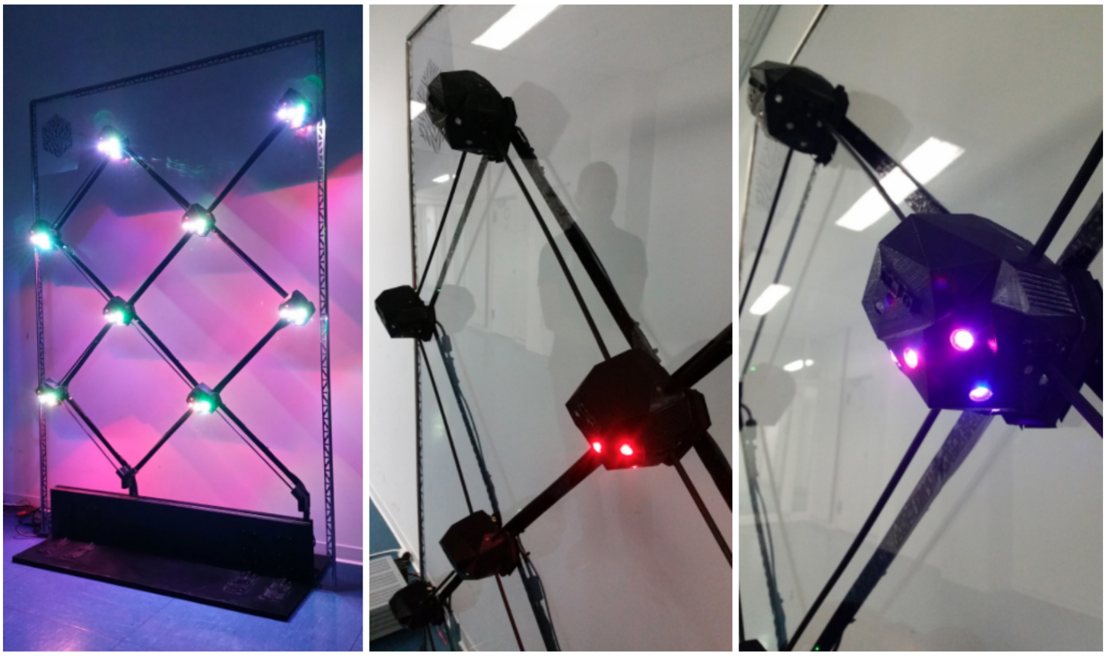


Figure 123: Nodes at 2D diagrid intersections.

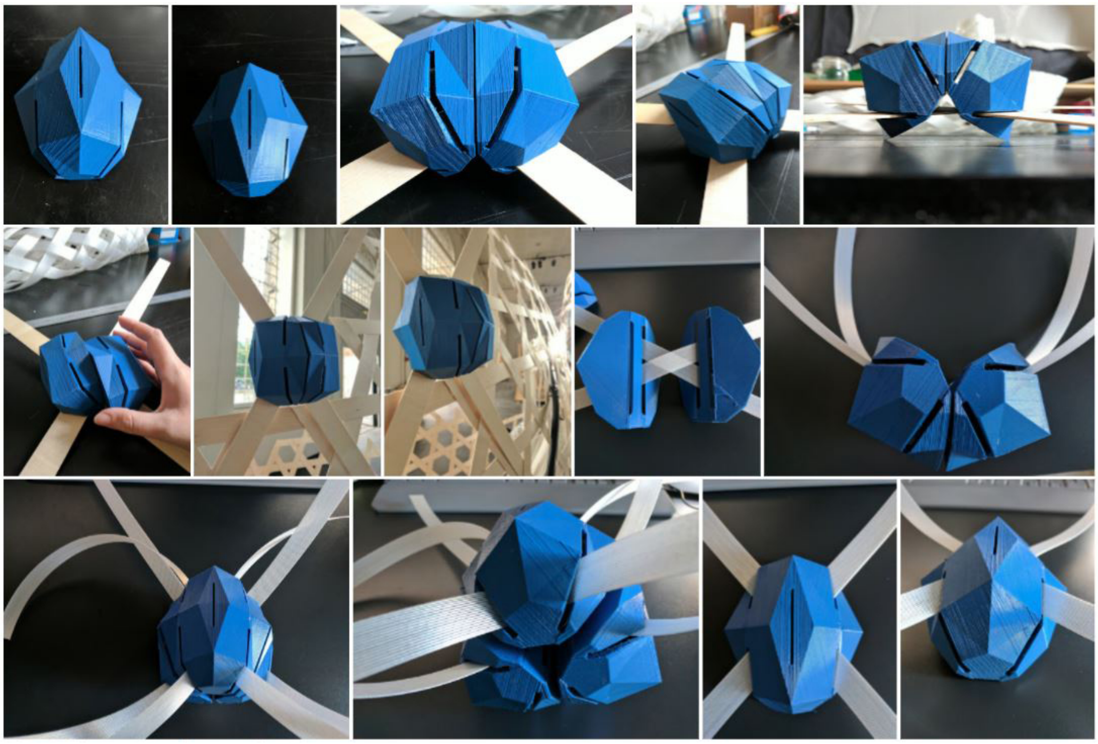


Figure 124: Nodes at braid intersections, both stiff and flexible filaments, both 2D and 3D.

Figure 125: Modules that use magnets to create temporary connections in a group of flexible braids.

Figure 126: Electronics integrated at filaments. (Left to right) Flat cables with water sensors, force sensor integrated between braid filaments, tubes for weight actuation braided triaxially into biaxial flat braid.

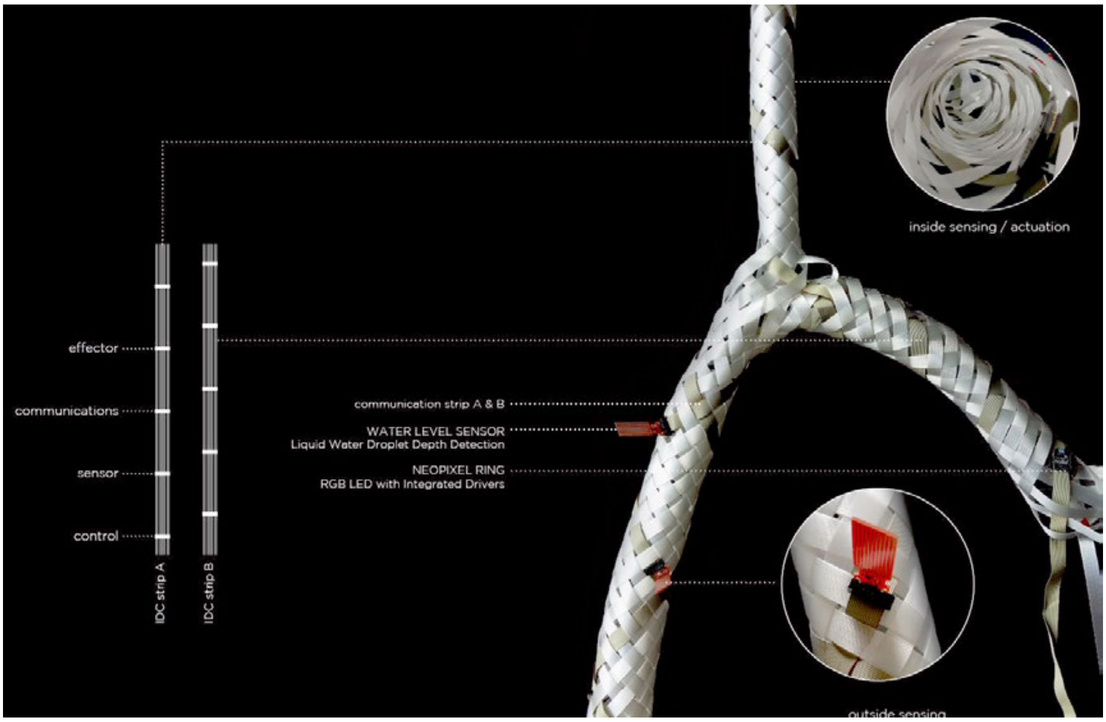


Figure 127: Sensors and LEDs on a cable acting as filament in a bifurcating tubular braid.

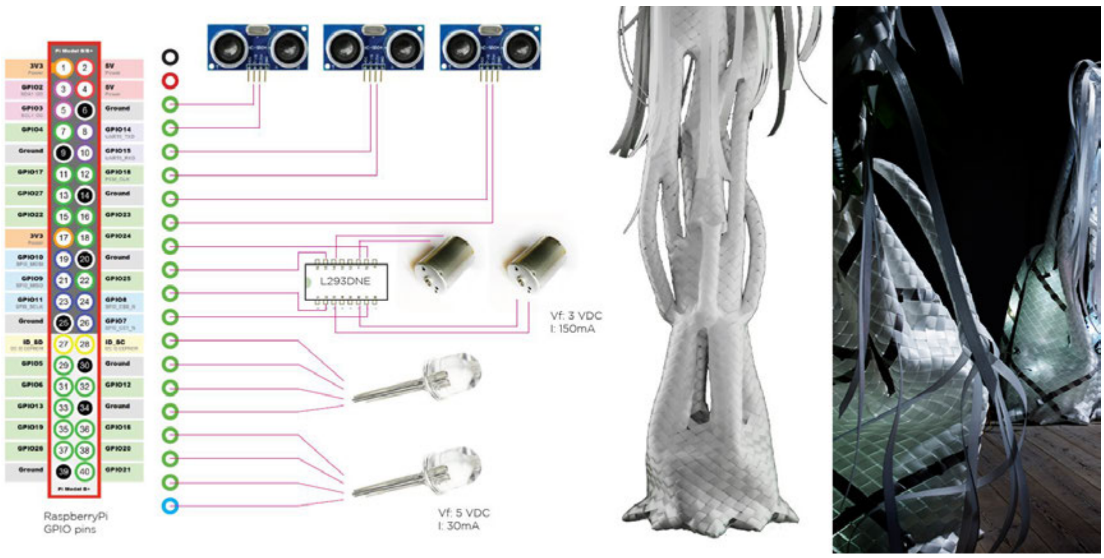


Figure 128: Sensors and LEDs on cables, integrated into braid by overlapping existing filaments in complex braided topolgies.

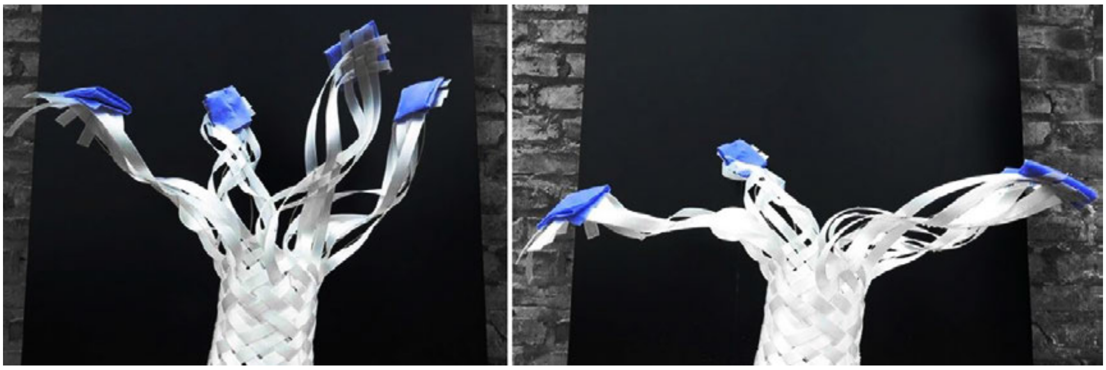


Figure 129: Point-load mechanical stress as actuation.

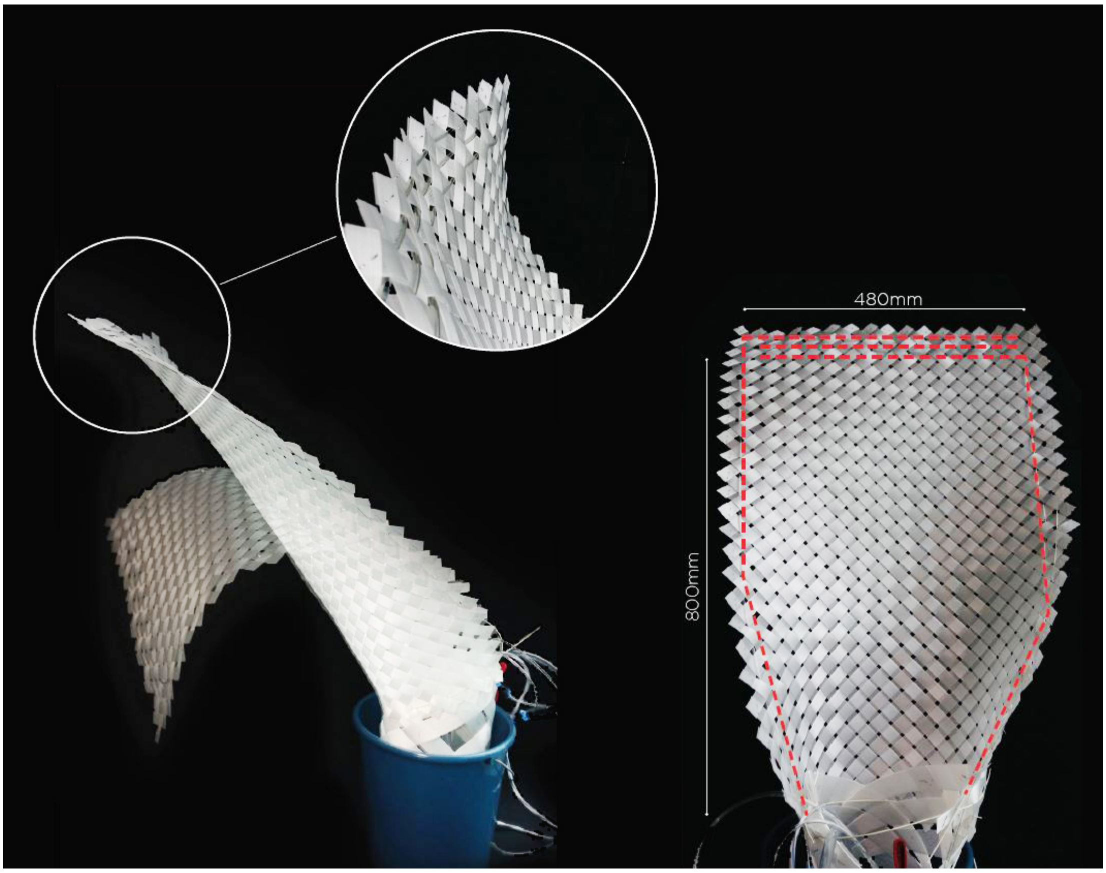


Figure 130: Distributed mechanical stress as actuation.

Figure 131: Actuators as mechanical supports that increase stiffness.

between node at braid allows the filaments to both rotate at translate, it functions similarly to the slotted filament approach in described in Sec. 2.2.3. If it allows for rotation at intersections, but not for translation, it functions similarly to the pin joints or elastic ties at individual filament intersections, described in Sec. 2.2.3. In both of these cases, the nodes would bring substantial increased stiffness to the overall braid, without much reducing its actuation capacity. It does however also bring the same impact of needing manual assembly during braiding, unbraiding, and rebraiding (as do all compact-module types). If the nodes are attached to the filaments in such a way that they cannot rotate at all at the intersections, then, although this would bring an extreme increase in stiffness to the overall braid, it would also make the braid function mechanically as a stiff diagrid, removing possibilities for actuation. (Although, perhaps at some points in the growth career, it is acceptable to 'freeze' the shape of the braids.) Also in this situation, the cases of the nodes would need to be able to withstand some mechanical force, as loads on the braid would stress its filaments to rotate at intersections. If the nodes restrict the ability to rotate, this load would then be transferred to the nodes.

Compact modules can also be made to perform some other secondary mechanical function, such as temporary connections between separate, adjacent braids (see Fig. 125).

Integrated cables Instead of compacting electronic components into localized modules, the components can be distributed along cables that are integrated into the braid as filaments (see Fig. 126). This strategy distributes the load added by the electronics, such that they are unlikely to cause any particular points of deformation in the braid, though the braid does still need to be stiff enough overall to support them.

Mechanically stiff electronic elements that cannot be loaded with mechanical stress—such as sensors, LEDs, and control boards—can be connected to flexible ribbon cable and braided seamlessly into any braid comprised of filaments with wide, flat cross-sections. The ribbon cable can replace a mechanical filament in the braid (see Fig. 127), as long as the ribbon cable will not be compromised by the degree of mechanical stress with which that braid may be loaded. For braids that may be subjected to consequential amounts of mechanical stress, the ribbon cable (or other cable types) can be threaded through the braid along the path of an existing filament (see Fig. 128), leaving some lag in the cable so that any translations or rotations in the filament organization will not stress the cable.

For any electronic elements that are flexible themselves, the element can also be integrated into the braid, from its anchored position on the cable. In some cases—such as for force sensors—this integration into the braid will be important for its proper functioning (see Fig. 126, center).

Mechanical stress as actuation Loading can also be used as a form of actuation. Though the control for these actuation mechanisms is provided by electronic elements, the mechanisms themselves are mostly mechanical. For instance, if water weight is used as an actuator, the pumps used to control the presence of water, and therefore the application of mechanical stress, are of course electronic elements, but the tubes and sponges used to transport and hold the water are purely mechanical. Mechanical stress as actuation can be applied either locally in point-loads, or distributed over a braided surface. For the example of water weight at actuator, sponges can be used to provide point-loads (see Fig. 129), with water pumped to them via tubes. In this way, the actuators can deform mechanically isolated elements of the braid, such as flat braid branches connected to a central tubular braid via strip inversions at the point of bifurcation, creating a mechanical weak point that acts as a joint in the braid. Distributed loading can be applied for example by braiding tubes triaxially into an area of biaxial braid (see Fig. 126, right). This loading strategy can deform an entire braid surface evenly (see Fig. 130), and does not require mechanical joints in the filament organization of the braid.

In certain cases, actuation elements that in some positions apply loads to a braid can also mechanically support that braid, in other positions, increasing its overall stiffness. For example, this occurs when GFRP rods are threaded through a braid to be used as actuators (see Fig. 131). When the rods are in their actuated position, the apply mechanical stress to the braid, deforming it to have a wider diameter opening at the end of the braid tube. When the rods are in their resting position, they act as triaxial reinforcement to the braid tube, increasing the stiffness of the overall braid.

4.2.2. Braided structures incorporating plant material

The growing of plants in a variety of both typical and extreme braid conditions was tested, to determine the degree to which plant growth is receptive to braid. These tests can be seen in full in the *PTR1: Periodic Technical Report 1, Part B*, but here we discuss the results of the test where a plant was subjected to the most extreme braid conditions—growing inside a very dense tubular braid, where the diameter of the braid tube was too small for the plant's leaves, and the leaves were, at a certain point, manually forced through very small gaps in the braid surface. More specifically, a banana tree (*Musa paradisiaca*) was cultivated inside a dense 2D biaxial tubular braid comprised of flexible polymer strapping. The aboveground part of banana trees is a pseudostem with a type of growth that makes it possible for growth to proceed despite colliding with the braids inner surface (as opposed to deciduous trees and conifers). Plants are sensitive to various mechanical stimuli, such as touch. In many cases even contact with a soft obstacle (i.e., not completely stiff) can stop a plants growth. In our experiments we found that the banana tree was unable to lift a braid of that particular size, weight, and density. A lighter braid with larger openings may give a more promising results for mechanical actuation. Leaves that passed through the very dense braid surface did not develop and were in poor condition, however, new leaves developed successfully inside the braid. After removing the braid, these new leaves were able to rapidly change their position to their normal physiological orientation. So, although the leaves subjected to the most extreme conditions died, the overall plant survived the inhospitable situation, and was able to return to its normal condition after the inhospitable situation was rectified. This is an example how plants can adapt to new environments and adapt their shape to spatial restrictions instead of requiring that their environment allow for their 'default' growth structure.

Figure 132: Openings in braid support plant health by providing space for them to grow, as well as easy access to light in the environment.

Mechanical integration of access to growth space and ambient light Although we have shown plants to be quite resilient in several inhospitable braid surroundings, this is not the situation we want to normally provide to the plant, and want to by default offer it conditions

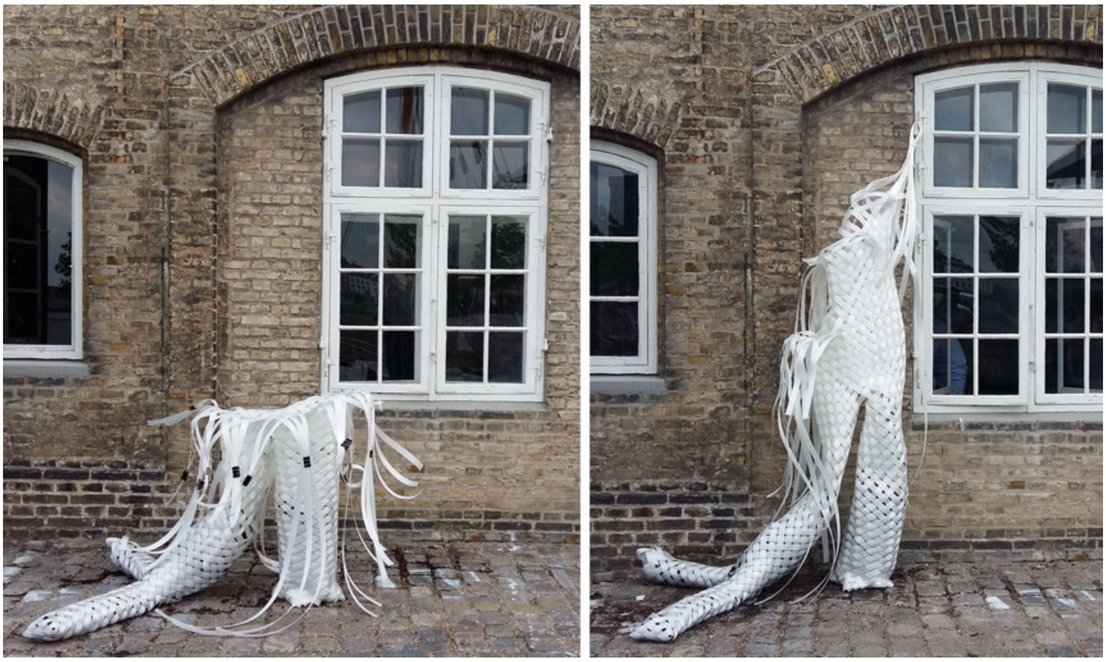


Figure 133: Two timesteps of a bifurcating tubular braid that was hand-braided to rise simultaneously to the plants growing inside the braid tube. The braid contains soil in its base, where the plant is rooted.

Figure 134: Several images of plants growing inside tubular braids that were hand-braided around them as they grew.

Figure 135: Integration of climbing plants with a fairly dense biaxial polymer braid (left), and a wood veneer triaxial braid with very large openings (right). Climbing plants can grow on either of these braid types. *Braids fabricated in part by Master's of Architecture students from KADK.*

Figure 136: Dense tubular braids with end-cap features can hold soil for planting, or, if lined with an industrial moisture barrier, can hold water reserves that can be pumped to plants when needed, via the GEM system for maintaining plant health (see Sec. 3.2.7).

Figure 137: The process of filling an industrial tubular braid with soil and seeds.

Figure 138: Growth of cress out of an industrial tubular braid.

Figure 139: A black elastic casing for soil, stretched inside the core of a tubular braid. *Fabricated in part by Master's of Architecture students from KADK.*

Figure 140: A topologically complex triaxial braid incorporating irregular cells, with elastic patches for soil infilling certain cells. *Fabricated in part by Master's of Architecture students from KADK.*

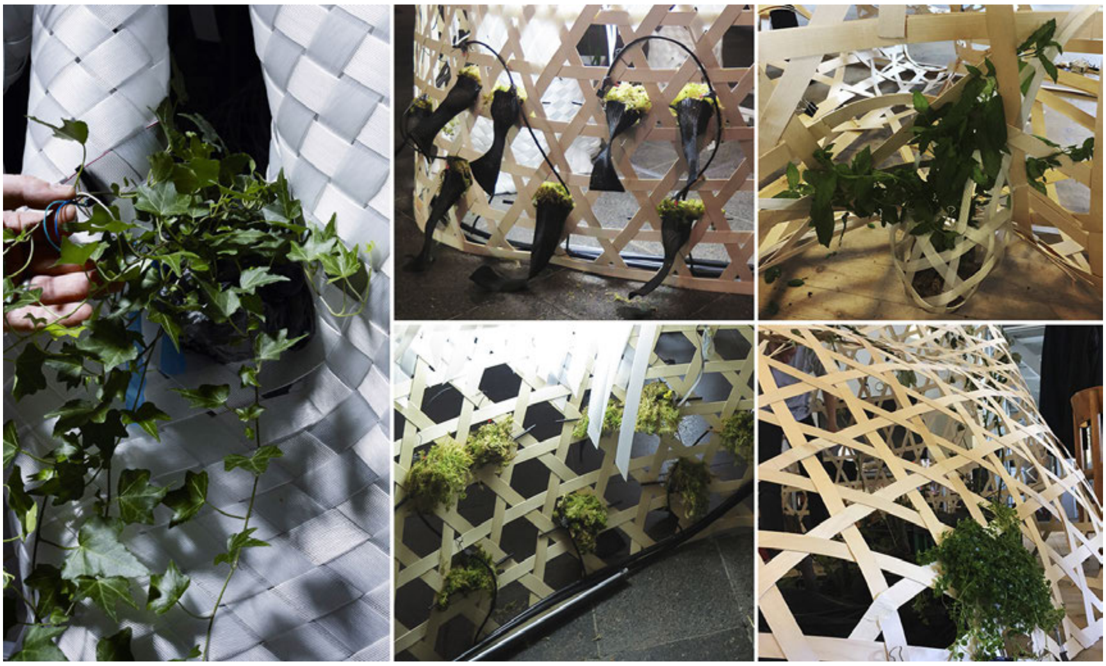


Figure 141: The incorporation of soft pots into braids. *Fabricated in part by Master's of Architecture students from KADK.*

Figure 142: The incorporation of stiff pots into braids. *Fabricated in part by Master's of Architecture students from KADK.*

that support its general health. It is of course evident that, to support plant health, the plants need access to certain resources such as light, nutrients, and water, as well as space to grow (see Fig. 132). This growing space can be provided for instance through openings in the mechanical scaffold—i.e., large spaces between neighboring filaments in a braid—or by having an open top on a braid tube, out from which a plant can grow. This requirement of course has a significant impact of the mechanical performance of the *flora robotica* artifacts. Strategies for stiffening braids while incorporating large gaps between filaments are discussed throughout Sec. 2.2, and the integration of these strategies with the fabrication constraints of the braiding machine is discussed in Sec. 2.4.

Another strategy to provide growing space and light access to plants is to have the artificial growth of the braid occurring simultaneously or consecutively to the natural growth of the plants. This was studied by continuously hand-braiding very densely braided tubular braids around plants that were growing inside them, such that the braiding rate matched the rate of plant growth and occurred simultaneously to it. The investigation was carried out successfully. (See timesteps of braid in Fig. 133 and views of the plants inside in Fig. 134).

For climbing plants (see Fig. 135), very large openings in the braid are not always needed (see Fig. 135, right), as long as the gaps between filaments are at least large enough that plants can grow in and out of the braid surface, ensuring exposure to needed light resources.

Mechanical integration of soil and water Other resources needed for natural growth—in particular water and nutrients provided via soil—are heavy, and can have a significant impact on the mechanical properties of braids. If located in the base of a very dense tubular braid with end-cap feature at the base, the braid base can be used as a container for planting soil, and even—with an additional layer for sealing—as a container to hold water reserves (see Fig. 136). This weight can be used as a structural anchor, playing a role similar to that of a typical structural foundation (see example of this usage in Fig. 133). Instead of being localized in a foundation element, soil resources can be distributed over a braid, using one of several distinct strategies. The first is by containing the soil in dense tubular braids of small diameter (see Fig. 137), as long as the gaps in the dense braid will still allow small plants like cress to grow through (see Fig. 138). These narrow tubular braids, once filled with soil and seeds, can be integrated into larger braids by either forming a 'braid of braids' (see Sec.2.2) or by integrating this narrow braid into a larger braid with large gaps between neighboring filaments. Because these narrow braids are fairly stiff when filled, they could potentially provide some mechanical reinforcement to larger braids into which they are integrated. The second strategy to distributing soil weight throughout the braid is very similar in principle, but more versatile in its possible implementations. It is enacted by containing soil in soft elastic containers that are stretched in the hollow core of a tubular braid, with fasteners to that braid that also function as sockets (see Fig. 139), from which plants much larger than cress can grow. The third strategy is somewhat less distributed in the allotment of mechanical stress. It is to contain soil in a group of localized secondary mechanical elements, such as soft secondary braids (see Fig. 141), or stiff potting elements (see Fig. 142). If stiff elements are used, they may also provide some mechanical reinforcement to the braid. In the final strategy, soil can be placed in elastic patches that act as infill on the cells of large braid with large gaps between filaments (see Fig. 140). Such patches could potentially perform a structural role to increase the stiffness of the overall braid. If filaments of the braid are extremely mechanically stressed, rather than the filaments translating or rotating substantially, the elastic patches will be loaded in tension, and thereby will keep the filaments of the braid relatively in position.

4.2.3. Discussion: Comparing mechanical performance to conventional materials

Our system incorporates two elements that would not normally be considered conventional construction materials: plants and braid.

Braided structures are already found in many industrial applications where they prove resilient both in regards to strength and dynamic properties. The advantage of this system over existing industrial systems is the variety of braided topologies, and the capacity to transition from one topology to the other in the same braid structure. That means this modular robotic system is capable of producing a variety of braid morphologies in different materials. Morphologies with different materiality and various dynamic properties may open the way to many additional industrial applications and we imagine these lightweight dynamic structures embedded with sensing, actuating, and computing units as self-contained robotic entities. This way the concept of multiple interacting robots can be extended to a heavily distributed sensing and actuation system that combines concepts from ambient computing and soft robotics. In the literature, there are also a wide array of available predictive models for mechanical and structural behavior in braids (see Sec. 2.3.1), and we as well develop some of our own models (see Sec. 2.3).

It is less evident however that plants are as well equipped to compare to convential building materials. Although we do develop models of stiffening behavior in plants (see D2.3), we here discuss the larger problematic of predictive structural modeling for biohybrids in general.

Predictive structural modeling for biohybrid buildings If biohybrid structural systems are to be built for standard occupation, their features will need to be approved by regulatory bodies. Most of the above examples of publicly accessible structures either might be categorized by their authors as art installations, or are built in isolated terrain where governments might not enforce building code regulations. In order to systematically realize buildings for long-term occupancy with biological elements in a structural role, the biological portions will need to be demonstrated as fulfilling structural provisions of relevant local and international building codes [see 56, 17, 20, 21]. Models of structural behavior will be challenging for materials that are living or are biologically deposited directly on site, therefore including some degree of unpredictability. In the process of developing the aforementioned *Baubotanik* structures, experiments to define structural Youngs moduli for the stems of utilized plant species revealed an extremely wide gap in structural performance based on environmental conditions during growth [75].

To predict structural performance in living buildings, we find two categorical approaches in the literature to be evidently relevant, one being finite element analysis (FEA) and the other being various artificial intelligence methods. FEA, which is standard across engineering disciplines [54], is also used in biological sciences for the study of plant biomechanics, among other functions [23]. This application of FEA could be investigated for extension to biological material in buildings, carrying multi-story and live occupancy loads. FEA was used, in combination with material testing, to confirm the structural behavior and safety of the *Hi-Fy* pavilion's fungal mycelium brick structure, in a way that was sufficient to be accepted for temporary public occupancy [96, 118]. Further pursuing this approach with the goal to establish biological building blocks in construction, we propose that biohybrid organisms be comprehensively specified in terms of expected environmental conditions in relation to structural and other properties such as amount of bio-material produced or shadow cast. The resulting database could be fed into a general, centrally maintained registry, similar to the one setup for amino acid chains and proteins for synthetic biology by MIT's international competition on genetically engineered machines (iGEM). One step further, also considering robustness that can result from sets of biohybrid agents working together, biohybrid (sub-)systems could be specified accordingly. The robots, which can be well-specified to begin with, could also fulfill the task of measuring the plants' proper development in accordance with the provided registry information and communicate their findings like sensor networks throughout the system and to the human user, in case interference is required.

Though the mycelium in the example above was killed before the bricks were aggregated, the unknowns of the material still caused substantial variation in material performance during the building's short lifespan. After heavy rainfall, moisture affected the stiffness of the mycelium bricks in a way unanticipated by the engineers, causing large deformations, according to [118]. The most affected areas of the structure were rebuilt during the lifespan of the building, successfully enabling continued public occupancy.

For the second approach, of various artificial intelligence methods, there are examples in the literature used to predict the behavior of materials that are nonuniform or present other challenges (c.f., neural networks for concrete or 3-d prints [106, 100]; genetic programming for limestone or geopolymers [9, 97]. Such methods could be investigated for predicting the structural performance of biological material that is alive or is deposited *in situ*. The modeling techniques used in the context of self-organizing systems could possibly also be applied here; but we are not aware of any related work.

Structural performance of living plants There is some additional published literature on the evidence surrounding structural performance of living plants. Here we briefly review some the key plots and tables from the literature. Specifically, the following are presented below:

- A plot analytically comparing the structural performance over time (in years) of a specific type of living structure to the same type of structure built from two conventional materials, concluding that the living structure increases in performance over time, while the others decrease (see Fig. 143 [124]).
- A plot comparing the stiffness and density of one type of living plant to conventional building materials. A key takeaway is that the stiffness and density change significantly over time (see Fig. 144 [124]). The plant species plotted here is far from the stiffest available; evidently, if living mature trees were compared in this plot, their performance would be substantially different.
- A plot documenting and comparing experiment results for the E-modulus of stems of woody plants grown in lab environments to those grown outdoors (see Fig. 145 [76]).
- A plot documenting and comparing experiment results for the failure types present in stems of woody plants grown in different environments (see Fig. 146 [76]).
- A table comparing the advantages (structural and otherwise) of the different plant species that are commonly used for manual shaping of plants and trees (see Fig. 147 [83], republished in [137]).

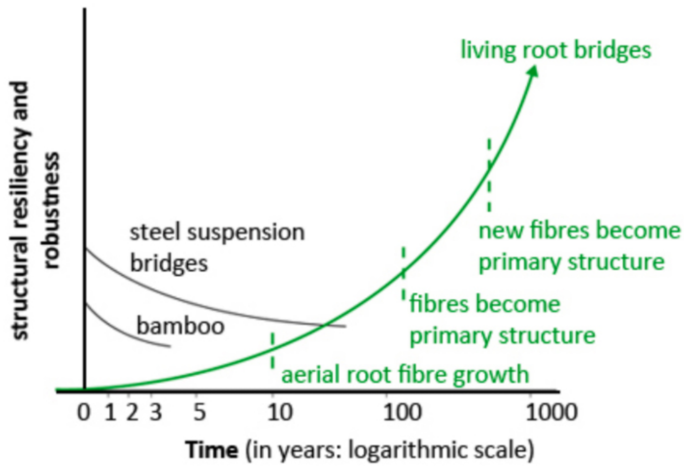


Figure 143: As quoted from the source in the literature: "Structural resiliency time chart ...[Living Root Bridges demonstrate] extraordinary structural and socio-ecological resilience" [124]

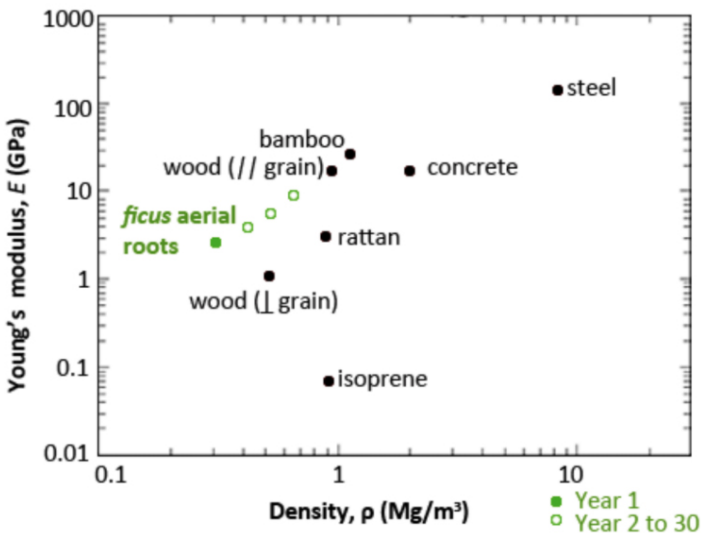


Figure 144: As quoted from the source in the literature: "A material property chart, which estimates the stiffness and density of Ficus aerial roots in comparison to contemporary construction materials ... Modulus Density chart ... (Modified and redrawn) *Ashby M., Shercliff H. and Cebon D. Materials Engineering, Science, Processing and Design, Elsevier, Pg 57, 2007* ... The author recognizes that the stiffness and density values of Ficus plant specie are time dependent, vary with local conditions and need precise scientific tests for validation." [124], based on [5].

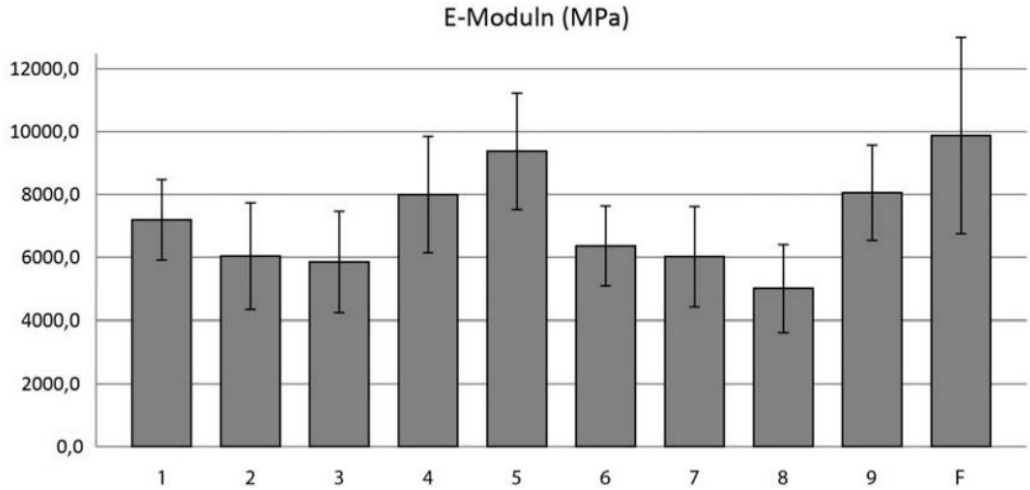


Figure 145: As quoted from the source in the literature (German language), follwed by its translation: "Die anhand von Vierpunktbiegungen ermittelten strukturellen E-Moduln im mittleren Achsendrittel . . . E-Moduln im mittleren Achsenabschnitt (F īm Freiland gewachsene Triebe) . . . Die je Kammer bzw. Anzuchtvariante berechneten Durchschnittswerte liegen zwischen 5.000 und 10.000 MPa, einzelne Werte im Bereich zwischen 3.000 und 13.000 MPa. Wie bereits erwhnt, wurden auch im Freiland gewachsene Triebe in die Untersuchung einbezogen (F). Die bei den Kontrollpflanzen (Kammer 9) ermittelten Werte lagen mit durchschnittlich 8.000 MPa (+/- 1.500 MPa) fast 2.000 MPa unter den Werten der im Freiland gewachsenen Triebe, bei denen jedoch eine besonders groe Streuung zu verzeichnen ist (10.000 MPa +/- 2.500 MPa). Die in Kammer 4 (Schattiergewebe) ermittelten Werte waren mit den Kontrollen so gut wie identisch, diejenigen der mit transparenter Folie umhllten Pflanzen (Kammer 5) lagen mit 9.400 MPa (+/- 1.800 MPa) zwischen den Kontrollen und den Freilandpflanzen. In allen anderen Kammern lagen die Werte durchschnittlich unter denjenigen der Kontrollen. Bei Umhllung der Achsen mit lichtdichter Folie ergaben sich Werte von 5.000 MPa (+/- 1.400 MPa), bei Umhllung mit Filterfolien (Kammern 2 und 7) unabhngig von der Dngung Werte von 6.000 MPa (+/- 1.700 MPa). Die bei insgesamt gefiltertem Licht gewachsenen Pflanzen zeigten Werte um 7.000 MPa (Kammer 1 / Lee #707) bzw. 6.400 MPa (Kammer 6 / Lee #707 zus. Dngung; jeweils ca. +/- 1.400 MPa) bzw. 6.000 MPa (Lee #707 + #179 / Kammer 3)." or "*The structural moduli of elasticity in the middle third of the axis determined by four-point bends . . . E-modules in the middle intersection (F s̄hoots grown in the field) . . . The calculated per chamber or cultivation variant Average values are between 5,000 and 10,000 MPa, individual values in the range between 3,000 and 13,000 MPa. As already mentioned, shoots grown in the field were also grown included in the study (F). The values determined for the control plants (chamber 9) averaged 8,000 MPa (+/- 1.500 MPa) nearly 2,000 MPa below the values of the shoots grown in the field, however, where there is a particularly large dispersion (10,000 MPa +/- 2,500 MPa). The values obtained in chamber 4 (shading tissue) were so good with the controls as identical, those of the transparent foil enveloped plants (chamber 5) were with 9,400 MPa (+/- 1,800 MPa) between the controls and the outdoor plants. In all others Chambers were on average below those of the controls. When serving the Axes with a light-tight foil gave values of 5,000 MPa (+/- 1,400 MPa), when encased with filter foils (chambers 2 and 7) regardless of the fertilization values of 6,000 MPa (+/- 1.700 MPa). The plants grown in total filtered light showed values 7,000 MPa (Chamber 1 / Lee #707) and 6,400 MPa (Chamber 6 / Lee #707 together fertilization, respectively +/- 1.400 MPa) or 6,000 MPa (Lee #707 + #179 / Chamber 3).*" [76]

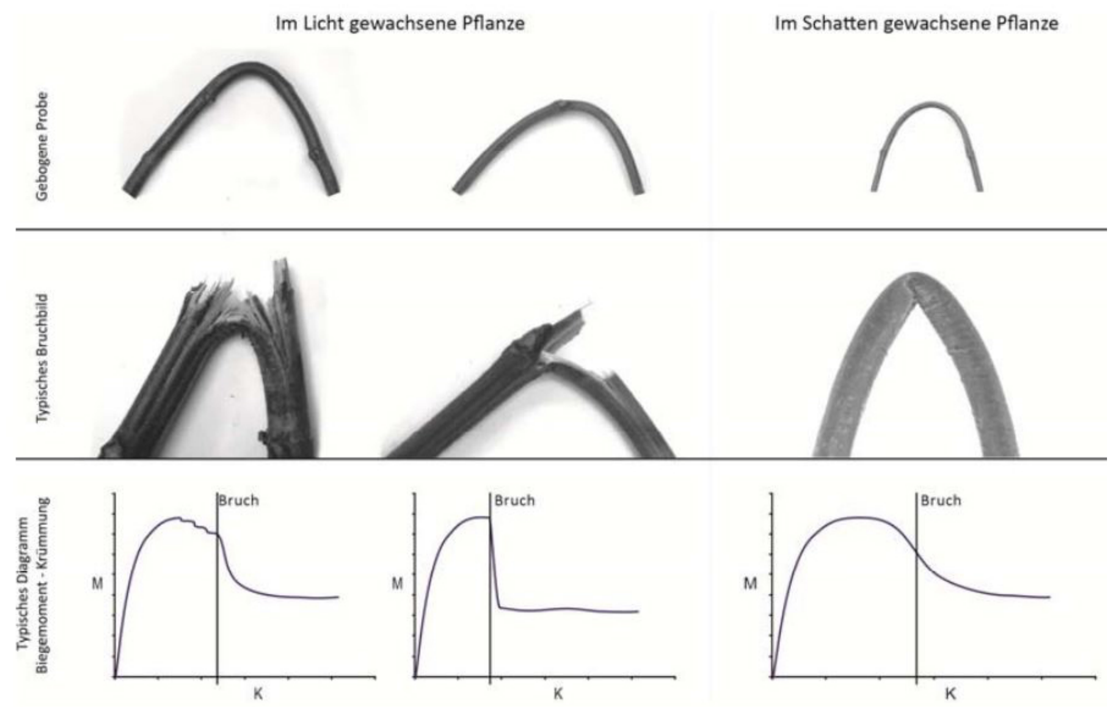


Figure 146: As quoted from the source in the literature (German language), follwed by its translation: "Versagenstypen und Bruchverhalten ... Gebogene, gebrochene, bzw. genickte Proben der jeweiligen Achsenabschnitte. Ganz unten: zugehriges Biegemoment-Krmmungs-Diagramm ... Bei den Bruchversuchen mit 2-Punkt-Biegung ergaben sich drei unterschiedliche Versagensmuster. Vor allem in den basalen Bereichen trat hufig ein zhes Brechen auf, dass sich durch Vorversagensereignisse (Riss einzelner Fasern) ankndigte (links). In den apikalen Bereichen kam es hufiger zu einem pltzlichen Bruch, bei dem die Achse bis zur Mitte quer einriss und unmittelbar darauf folgend lngs aufspaltete. Das Biegemoment-KrmmungsDiagramm zeigt hier einen pltzlichen Abfall (Mitte). Zum Dritten trat bei einigen Pflanzen als Versagen kein Brechen sondern ein Abknicken auf. Bei diesem Versagenstyp lsst sich der Versagenspunkt nicht immer eindeutig bestimmen, da das BiegemomentKrmmungs-Diagramm keinen eindeutigen Punkt erkennen lsst, sondern einen kontinuierlichen Verlauf zeigt. Daher wurde hier der Wendepunkt der Kurve als Versagenspunkt festgelegt (rechts)." or "*Failure types and fracture behavior ... Curved, broken, or creased samples of the respective intercept. At the bottom: associated bending moment-curvature diagram ... Two-point bending fracture tests revealed three different failure patterns. Especially in the basal areas was often a tough break on that through pre-failure events (crack of single fibers) announced (left). In the apical areas were more likely to experience a sudden break, with the axis centered transverse tear and immediately split longitudinally. The bending moment-curvature diagram shows here a sudden drop (middle). Third came with some plants as failure no breaking but a kinking on. In this failure type the failure point can not always be determined unambiguously, because the bending moment curve diagram does not show a clear point, but a continuous one course shows. Therefore, here the inflection point of the curve was set as a failure point (right).*" [76]

	Plane tree (*Platanus acerifolia*)	Willow (*Salix babylonica*)	Ficus (*Ficus benjamina*)	Beech tree (*Fagus sylvatica*)	Ash (*Fraxinus excelsior*)
Structural resistance	Very High	Low to medium	Medium	Very High	High
Growth speed	Medium to fast	Fast	Medium to fast	Slow to medium	Medium to high
Inosculation possibility	Very high	Medium	Very high	Very High	Very high (screw bond)
Bending and "tree shaping" possibilities	High	Very High	High	Medium	Very High
Origin	Hybrid, common in Europe	Australia	Asia	Europe	Europe and occidental Asia
Scarcity	Common	Common	Common	Common	Common
Additional advantage		Less sensible to diseases and parasites			Less sensible to diseases and parasites

Figure 147: Comparison of selected species that might be used for tree shaping or for root shaping. Table by [83], republished in [137]

4.3 Performative properties of bio-mechanical hybrids

Beyond structural and façade functions, there are additional perfomative functions that living bio-mechanical hybrids can deliver. Beyond the evident possibility for partially grown elements to serve interior use functions and similar (e.g., partition walls, furniture, benches), there are several further functions and advantages evidenced in the literature, which are not offered by traditional construction materials. The following are those we determine to be achievable by the *flora robotica* system:

1. once constructed, a living structure can last for centuries with minimal maintenance;
2. a living structure can thrive in environments where standard construction materials decay very quickly, such as regions with monsoons and very high humidity;
3. supporting a range of plants and animals present naturally in local habitats, with the aim of increasing biodiversity [cf. urban biodiversity, 37];
4. mitigating the urban heat island effect [128];
5. managing urban stormwater [127]; and
6. importantly, a living structure can conduct self-repair if it becomes damaged.

4.3.1. Self-repair: the planned demonstrator

As evidenced in the literature documenting the *Living Root Bridges* [124], living bridges have been demonstrated to structurally outlast steel suspension bridges in the area due to high levels of moisture and dynamic loads such as flash floods. A contributing factor to this resiliency is that living structures can self-repair and traditional structures cannot. According to [124], the same plants used to construct the *Living Root Bridges* are also used to repair damaged steel cable bridges in the area, which often do not last more than 10 or 15 years, while the living bridges last for a century or more.

Within the project we want to showcase an integrated demonstrator of our approaches, on a small scale (see Fig. 148). Initially we produce a braided scaffold with the braiding robot supported by the VMC approach and position robotic nodes (Fig. 148-1). Appropriately selected plant species are grown along these structures and their growth is steered by the robotic nodes (Fig. 148-2). This could include the detection of passages frequently used by humans or the definition of windows that, hence, need to be avoided by the plants. The plants are monitored by our sensors on the braid and the plants. As a benchmark we plan a windowed wall and punch a hole into our grown living architecture (Fig. 148-3). The hole needs to be repaired autonomously by the system. Within the window area, plant growth is still prohibited. This benchmark is completed successfully once the hole is self-repaired while the window is still free of plants (Fig. 148-4). In this way we would prove one main advantage of living architecture, which is adaptive self-repair on site.

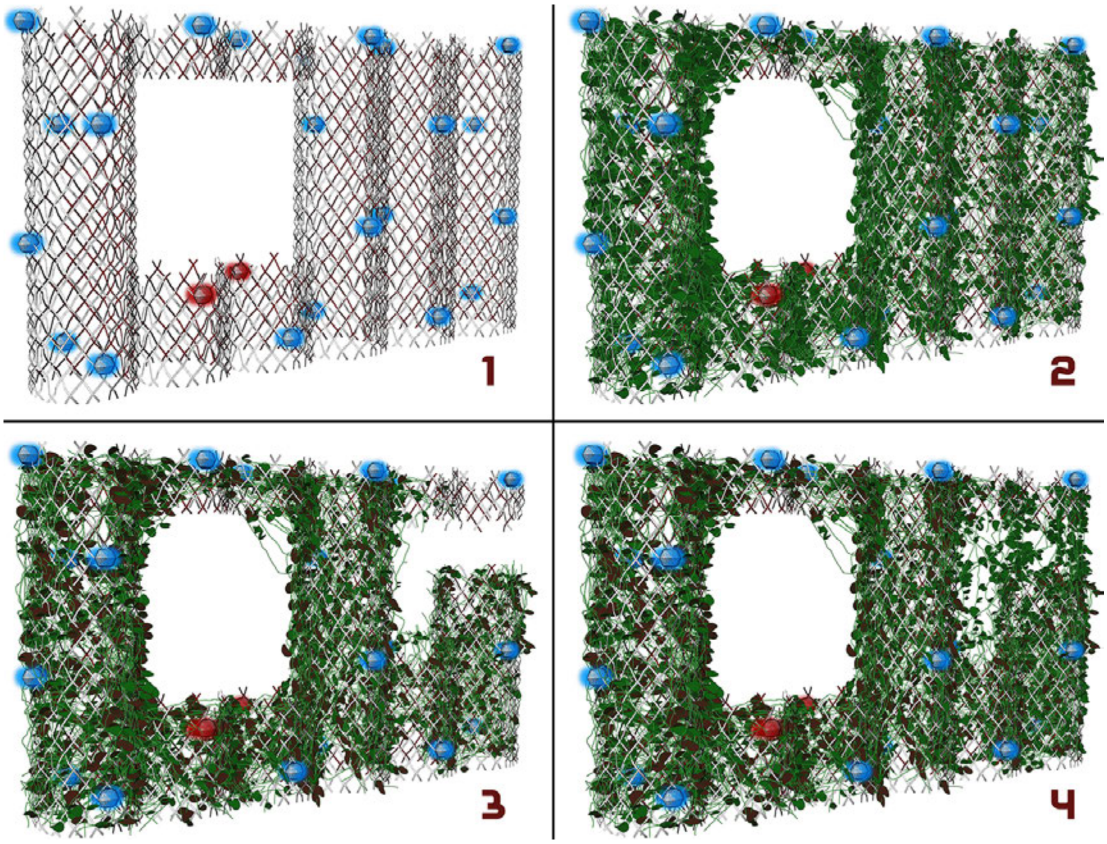


Figure 148: The planned demonstrator to showcase one of living structures' greatest assets compared to traditional structures: the ability to self-repair. (From 1, to 4) The braided wall without any plant growth; the fully grown living wall, the damaged living wall, where both plant and mechanical structural elements are compromised; the final self-repaired wall, where the living elements replaced not only the damaged plant growth, but the damaged mechanical braid.

5 Conclusion

In this report, we have presented the development of braid as the central construction logic of *flora robotica*, including the investigations of its mechanical properties and the understandings of its reciprocal relationships to other parts of the project and to architectural propositions. We have envisioned speculative architectural growth careers, and presented an example of simulated growth that could feasibly be produced in the real-world by the project components at their current stage of development. We have presented the existing evidence surrounding grown building components and proposed new solutions specific to *flora robotica*. We have analyzed the structural and façade performance potential of grown building components in comparison to conventional construction materials, and identified additional categories of performance in which grown components offer significant advantages over conventional ones. We have briefly discussed a planned demonstrator, which focuses on a key example of such an advantage: Self-repair of a damaged living structure.

References

[1] 2018. Image of the Rostock Willow Church [62]. IGA2003 Rostock Weidendom.jpg, published on Wiki Commons by user Schiwago under the license CC BY 2.5. https://en.wikipedia.org/wiki/2003_World_Horticultural_Exposition#/media/File:IGA2003_Rostock_Weidendom.jpg.

[2] Ergun Akleman, Jianer Chen, Qing Xing, and Jonathan L Gross. Cyclic plain-weaving on polygonal mesh surfaces with graph rotation systems. In *ACM Transactions on Graphics (TOG)*, volume 28, page 78. ACM, 2009.

[3] Joey Anetsberger and Josh Bongard. Robots can ground crowd-proposed symbols by forming theories of group mind. *Proceedings Alife XV*, 2016. doi: 10.7551/978-0-262-33936-0-ch109. URL http://dx.doi.org/10.7551/978-0-262-33936-0-ch109.

[4] Ronald C. Arkin and Magnus Egerstedt. Temporal heterogeneity and the value of slowness in robotic systems. In *2015 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 1000–1005. IEEE, 2015. doi: 10.1109/ROBIO.2015.7418902. URL http://dx.doi.org/10.1109/ROBIO.2015.7418902.

[5] Michael F. Ashby, Hugh Shercliff, and David Cebon. *Materials: engineering, science, processing and design*. Butterworth-Heinemann, 2013.

[6] Katherine L. Baldwin, Allison K. Strohm, and Patrick H. Masson. Gravity sensing and signal transduction in vascular plant primary roots. *American Journal of Botany*, 100(1): 126–142, 2013. ISSN 00029122. doi: 10.3732/ajb.1200318.

[7] František Baluška, Stefano Mancuso, Dieter Volkmann, and Peter Barlow. The root-brain' hypothesis of Charles and Francis Darwin. *Plant Signaling & Behavior*, 4(12):1121–1127, 2009. ISSN 1559-2324. doi: 10.4161/psb.4.12.10574. URL http://www.tandfonline.com/doi/abs/10.4161/psb.4.12.10574.

[8] Renaud Bastien and Yasmine Meroz. The kinematics of plant nutation reveals a simple relation between curvature and the orientation of differential growth. *PLOS Computational Biology*, 12(12):e1005238, 2016.

[9] Adil Baykasolu, Hamza Gll, Hanifi anak, and Lale zbakr. Prediction of compressive and tensile strength of limestone via genetic programming. *Expert Systems with Applications*, 35(12):111 – 123, 2008. ISSN 0957-4174. doi: https://doi.org/10.1016/j.eswa.2007.06.006. URL http://www.sciencedirect.com/science/article/pii/S0957417407002163.

[10] Anna-Lena Beger, Manuel Löwer, Jörg Feldhusen, Jürgen Prell, Alexandra Wormit, Björn Usadel, Christoph Kämpfer, Thomas-Benjamin Seiler, Henner Hollert, Franziska Moser, et al. Tailored natural components–functional geometry and topology optimization of technical grown plants. In *11th World Congress on Structural and Multidisciplinary Optimisation, WCSMO-11*, 2015.

[11] Sascha Bohnenberger, Klaas de Rycke, and Agnes Weilandt. Lattice spaces: Form optimisation throgh customization of non developable 3d wood surfaces. 2011.

[12] Janet Braam. In touch: plant responses to mechanical stimuli. *New Phytologist*, 165(2): 373–389, 2005.

[13] Winslow R. Briggs. Phototropism: some history, some puzzles, and a look ahead. *Plant physiology*, 164(1):13–23, 2014.

[14] G Broadbent. The ecology of the mudhif. *Eco-architecture II: Harmonisation Between Architecture and Nature*, 113:1115, 2008.

[15] M Calkins. A living structure: The willow dome at the real goods solar living center. *Landscape Architecture*, 90(10):42–45, 2000.

[16] Punarbasu Chaudhuri, Subarna Bhattacharyya, and Alok Chandra Samal. Living root bridge: A potential no cost eco-technology for mitigating rural communication problems. *Int. J. Exp. Res. Rev*, 5:33–35, 2016.

[17] Francis DK Ching and Steven R Winkel. *Building Codes Illustrated: A Guide to Understanding the 2015 International Building Code*. John Wiley & Sons, 2016.

[18] John M. Christie and Angus S. Murphy. Shoot phototropism in higher plants: New light through old concepts. *American Journal of Botany*, 100(1):35–46, 2013. ISSN 00029122. doi: 10.3732/ajb.1200340.

[19] Sharon Gamson Danks. Green mansions: Living willow structures enhance children's play environments. *Children, Youth and Environments*, 13(1), 2003.

[20] DG Enterprise and Industry and Joint Research Centre. B1 - the eurocodes: Implementation and use. Technical report, Enterprise and Industry Directorate General (DG ENTR) and the Joint Research Centre (JRC), 2008.

[21] S. Dimova, M. Fuchs, A. Pinto, B. Nikolova, L. Sousa, and S. Iannaccone. Jrc: Policy support document: State of implementation of the eurocodes in the european union. Technical report, Publication office of the European Union, 2015.

[22] Mohammad Divband Soorati and Heiko Hamann. Robot self-assembly as adaptive growth process: Collective selection of seed position and self-organizing tree-structures. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2016)*, pages 5745–5750. IEEE, 2016. doi: 10.1109/IROS.2016.7759845. URL `http://dx.doi.org/10.1109/IROS.2016.7759845`.

[23] ER Dumont, Ian R Grosse, and Graham J Slater. Requirements for comparing the performance of finite element models of biological structures. *Journal of theoretical biology*, 256 (1):96–103, 2009.

[24] Ecosistema Urbano, Belinda Tato, Jose Luis Vallejo, Diego Garca-Setin, Ignacio Prieto, Maria Eugenia Lacarra, David Delgado, David Benito, Jaime Eizaguirre, Patricia Lucas, Ana Lpez, Asier Barredo, Laura Casas, Fabricio Pepe, Michael Moradiellos, Ignacio Lpez, Tectum Ingeniera, S.L., and Grupo Entorno, S.A. Eco boulevard in vallecas. Images by the architect and republished in [64], 66, 2007. Building in Vallecas, Madrid, Spain.

[25] Axel Erlandson. Basket tree. Images by author published in [109], republished in [76], 37, c. 1940s. Built structures originally at Tree Circus in Scotts Valley, California, USA, currently at Gilroy Gardens in Gilroy, California, USA.

[26] Wilma Erlandson. *My Father "Talked to Trees"*. W. Erlandson, 2001.

[27] Gemma Farré, Dieter Blancquaert, Teresa Capell, Dominique Van Der Straeten, Paul Christou, and Changfu Zhu. Engineering complex metabolic pathways in plants. *Annual review of plant biology*, 65:187–223, 2014.

[28] Donald P. Fraser, Scott Hayes, and Keara A. Franklin. Photoreceptor crosstalk in shade avoidance. *Current Opinion in Plant Biology*, 33:1–7, 2016. ISSN 13695266. doi: 10.1016/j.pbi.2016.03.008. URL http://dx.doi.org/10.1016/j.pbi.2016.03.008.

[29] Bonnie Gale. The potential of living willow structures in the landscape. Master's thesis, State University of New York, College of Environmental Science and Forestry, 2011.

[30] Bonnie Gale. Living willow tunnel. Published in [29], 18, 2011. Built structure at Pierce's Park in Baltimore, Maryland, USA.

[31] Vinicius Costa Galvão and Christian Fankhauser. Sensing the light environment in plants: Photoreceptors and early signaling steps. *Current Opinion in Neurobiology*, 34(Figure 1): 46–53, 2015. ISSN 18736882. doi: 10.1016/j.conb.2015.01.013.

[32] Matthew Gandy. The ecological facades of Patrick Blanc. *Architectural Design*, 80(3): 28–33, 2010.

[33] Barry Gardiner, Peter Berry, and Bruno Moulia. Review: Wind impacts on plant growth, mechanics and damage. *Plant Science*, 245:94–118, 2016.

[34] Ernesto Gianoli. The behavioural ecology of climbing plants. *AoB PLANTS*, 7(1):1–11, 2015. ISSN 20412851. doi: 10.1093/aobpla/plv013.

[35] Joseph Gibaldi. *MLA style manual and guide to scholarly publishing*, volume C10 45. Modern Language Assn. of Amer., 2008.

[36] Manuela Giovannetti, Luciano Avio, Paola Fortuna, Elisa Pellegrino, Cristiana Sbrana, and Patrizia Strani. At the root of the wood wide web: self recognition and nonself incompatibility in mycorrhizal networks. *Plant signaling & behavior*, 1(1):1–5, 2006.

[37] Mark A Goddard, Andrew J Dougill, and Tim G Benton. Scaling up from gardens: biodiversity conservation in urban environments. *Trends in Ecology & Evolution*, 25(2):90–98, 2010.

[38] Ezekiel Golan. Method and a kit for shaping a portion of a woody plant into a desired form, February 12 2008. US Patent 7,328,532.

[39] Charlotte M. M. Gommers, Eric J. W. Visser, Kate R. St. Onge, Laurentius A. C. J. Voesenek, and Ronald Pierik. Shade tolerance: When growing tall is not an option. *Trends in Plant Science*, 18(2):65–71, 2013. ISSN 13601385. doi: 10.1016/j.tplants.2012.09.008. URL http://dx.doi.org/10.1016/j.tplants.2012.09.008.

[40] Murali Gopal and Alka Gupta. Microbiome selection could spur next-generation plant breeding strategies. *Frontiers in Microbiology*, 7:1971, 2016. ISSN 1664-302X. doi: 10.3389/fmicb.2016.01971. URL https://www.frontiersin.org/article/10.3389/fmicb.2016.01971.

[41] E. W. Gudger. Stitching wounds with the mandibles of ants and beetles. *Journal of the American Medical Association*, 84:18611864, 1925.

[42] Qiaohang Guo, Eric Dai, Xiaomin Han, Stephen Xie, Eric Chao, and Zi Chen. Fast nastic motion of plants and bioinspired structures. *Journal of the Royal Society Interface*, 12 (110):20150598, 2015.

[43] Heiko Hamann, Mostafa Wahby, Thomas Schmickl, Payam Zahadat, Daniel Hofstadler, Kasper Stoy, Sebastian Risi, Andres Faina, Frank Veenstra, Serge Kernbach, et al. *flora robotica* – mixed societies of symbiotic robot-plant bio-hybrids. In *Computational Intelligence, 2015 IEEE Symposium Series on*, pages 1102–1109. IEEE, 2015.

[44] Heiko Hamann, Yara Khaluf, Jean Botev, M Divband Soorati, Eliseo Ferrante, Oliver Kosak, Jean-Marc Montanier, Sanaz Mostaghim, Richard Redpath, Jon Timmis, et al. Hybrid societies: challenges and perspectives in the design of collective behavior in self-organizing systems. *Frontiers in Robotics and AI*, 3, 2016. doi: 10.3389/frobt.2016.00014.

[45] Olivier Hamant. Widespread mechanosensing controls the structure behind the architecture in plants. *Current Opinion in Plant Biology*, 16(5):654–660, 2013. ISSN 13695266. doi: 10.1016/j.pbi.2013.06.006.

[46] Yasuko Hashiguchi, Masao Tasaka, and Miyo T. Morita. Mechanism of higher plant gravity sensing. *American Journal of Botany*, 100(1):91–100, 2013. ISSN 00029122. doi: 10.3732/ajb.1200315.

[47] Elliot W. Hawkes, Laura H. Blumenschein, Joseph D. Greer, and Allison M. Okamura. A soft robot that navigates its environment through growth. *Science Robotics*, 2(8), 2017. doi: 10.1126/scirobotics.aan3028. URL http://dx.doi.org/10.1126/scirobotics.aan3028.

[48] Mary Katherine Heinrich, Mostafa Wahby, Mohammad Divband Soorati, Daniel Nicolas Hofstadler, Payam Zahadat, Phil Ayres, Kasper Støy, and Heiko Hamann. Self-organized construction with continuous building material: Higher flexibility based on braided structures. In *Proc. of the 1st International Workshop on Self-Organising Construction (SOCO)*, pages 154–159. IEEE, 2016. doi: 10.1109/FAS-W.2016.43.

[49] Mary Katherine Heinrich, Mostafa Wahby, Mohammad Divband Soorati, Daniel Nicolas Hofstadler, Payam Zahadat, Phil Ayres, Kasper Støy, and Heiko Hamann. Self-organized construction with continuous building material: Higher flexibility based on braided structures. In *Foundations and Applications of Self* Systems, IEEE International Workshops on*, pages 154–159. IEEE, 2016.

[50] Robert Herman. Green roofs in Germany: yesterday, today and tomorrow. *Greening Rooftops for Sustainable Communities, Chigago*, pages 41–45, 2003.

[51] Daniel Nicolas Hofstadler, Mostafa Wahby, Mary Katherine Heinrich, Heiko Hamann, Payam Zahadat, Phil Ayres, and Thomas Schmickl. Evolved control of natural plants: Crossing the reality gap for user-defined steering of growth and motion. *ACM Transactions on Autonomous and Adaptive Systems (TAAS)*, 12(3):15, 2017.

[52] Sander W. Hogewoning, Emilie Wientjes, Peter Douwstra, Govert Trouwborst, Wim van Ieperen, Roberta Croce, and Jeremy Harbinson. Photosynthetic Quantum Yield Dynamics: From Photosystems to Leaves. *The Plant Cell*, 24(5):1921–1935, 2012. ISSN 1040-4651. doi: 10.1105/tpc.112.097972.

[53] Jon Hughes. Phytochrome cytoplasmic signaling. *Plant Biology*, 64(1):377, 2013.

[54] Thomas JR Hughes. *The finite element method: linear static and dynamic finite element analysis*. Courier Corporation, 2012.

[55] Shinichiro Inoue, Toshinori Kinoshita, and Kenichiro Shimazaki. Possible involvement of phototropins in leaf movement of kidney bean in response to blue light. *Plant physiology*, 138(4):1994–2004, 2005. ISSN 0032-0889. doi: 10.1104/pp.105.062026.

[56] International Code Council (ICC). International building code. *International Code Council, Inc.(formerly BOCA, ICBO and SBCCI)*, 2012.

[57] Mitchell Joachim. Bio city map and plugin ecology. *The Routledge Companion to Biology in Art and Architecture*, 2016.

[58] Dan Johnson. Grow-it-yourself furniture. *The Futurist*, 33(2):60, 1999.

[59] Marcel Kalberer and Micky Remann. *Das Weidenbaubuch: die Kunst, lebende Bauwerke zu gestalten*. At Verlag, 1999.

[60] Marcel Kalberer and Micky Remann. *Grüne Kathedralen: Die weltweite Wirkung wachsender Weiden*. AT Verlag, 2003.

[61] Marcel Kalberer and Sanfte Strukturen. Auerworld palast. Images by author and published in [29], 21, and [126], 20–21, 1998. Building in Auerstedt, Germany.

[62] Marcel Kalberer and Sanfte Strukturen. Willow church. Images published in [76], 48, and [126], 23, 2003. Building at the 2003 World Horticultural Exposition in Rostock, Germany.

[63] Matthew Kaplan and Elaine Cohen. Computer generated celtic design. *Rendering Techniques*, 3:9–19, 2003.

[64] Khrystyna Katola and Bohdan Goy. The “green architecture” definition development in modern projecting and building. *Środowisko Mieszkaniowe*, 2015.

[65] Fabian Kellermeier, Patrick Armengaud, Triona J Seditas, John Danku, David E Salt, and Anna Amtmann. Analysis of the Root System Architecture of Arabidopsis Provides a Quantitative Readout of Crosstalk between Nutritional Signals. *The Plant cell*, 26(4):1480–1496, 2014. ISSN 1532-298X. doi: 10.1105/tpc.113.122101. URL `http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4036566{&}tool=pmcentrez{&}rendertype=abstract`.

[66] Konstantin Kirsch. *Naturbauten aus lebenden Gehölzen*. OLV, Organischer Landbau-Verlag Lau, 1997.

[67] Konstantin Kirsch. Ash tree house or ash tree dome. Images by author and published in [29], 31, ca.1990. Built structure in Bauhaus, Germany.

[68] Konstantin Kirsch and Herrmann Fritz Block. Waldgartendorf. Images by author and published in [76], 50, 1993-1997. Built structures near Kassel, Germany.

[69] Manfred Köhler. Green facadesa view back and some visions. *Urban Ecosystems*, 11(4): 423, 2008.

[70] Ulrich Kutschera and Winslow R Briggs. Phototropic solar tracking in sunflower plants: an integrative perspective. *Annals of botany*, 117(1):1–8, 2016.

[71] Nathalie Leblanc-Fournier, Ludovic Martin, Catherine Lenne, and Mélanie Decourteix. To respond or not to respond, the recurring question in plant mechanosensitivity. *Frontiers in plant science*, 5:401, 2014.

[72] Andrew C. K. Lee and R. Maheswaran. The health benefits of urban green spaces: a review of the evidence. *Journal of Public Health*, 33(2):212–222, 2011. doi: 10.1093/pubmed/fdq068. URL https://doi.org/10.1093/pubmed/fdq068.

[73] Emmanuel Liscum, Scott K Askinosie, Daniel L Leuchtman, Johanna Morrow, Kyle T Willenburg, and Diana Roberts Coats. Phototropism: growing towards an understanding of plant movement. *The Plant cell*, 26(1):38–55, 2014. ISSN 1532-298X. doi: 10.1105/tpc.113.119727. URL http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3963583{&}tool=pmcentrez{&}rendertype=abstract.

[74] D. López-Pérez, P.U.S. Architecture, P.A. Press, A. Zaera-Polo, and S. Allen. *R. Buckminster Fuller: World Man*. Princeton Architectural Press, 2013. ISBN 9781616890940. URL https://books.google.dk/books?id=fceVuAAACAAJ.

[75] F. Ludwig, G. De Bruyn, M. Thielen, and T. Speck. Plant stems as building material for living plant constructions. In *Thibaut, B. (ed.) Proceedings of the 6th Plant Biomechanics Conference, French Guyana, France, Cayenne, 2009*, volume 405, 2009.

[76] Ferdinand Ludwig. Botanische Grundlagen der Baubotanik und deren Anwendung im Entwurf. Master's thesis, Institut Grundlagen Moderner Architektur und Entwerfen der Universitt Stuttgart, 2012.

[77] Ferdinand Ludwig. Baubotanik – designing with living material. *Materiality and Architecture*, page 182, 2016.

[78] Ferdinand Ludwig, Oliver Storz, Baubotanik research group, and Neue Kunst am Ried. Baubotanik footbridge. Images by author and published in [77], 184, 2005. Built structure in Wald-Ruhestetten, Germany.

[79] Ferdinand Ludwig, Cornelius Hackenbracht, Baubotanik research group, and Neue Kunst am Ried. Baubotanical Tower. Images by author and published in [81], 86, 2009. Building in Wald-Ruhestetten, Germany.

[80] Ferdinand Ludwig, Daniel Schönle, Ingenieurbüro Brocke, Christoph Roesler, and SecOp / GaLaTech. Platanenkubus Nagold (Nagold Tree Hub). Images by author and published in [76], 254–255, 2011. Building at the 2011 Landesgartenschau in Norderstedt, Germany.

[81] Ferdinand Ludwig, Hannes Schwertfeger, and Oliver Storz. Living systems: Designing growth in Baubotanik. *Architectural Design*, 82(2):82–87, 2012.

[82] Asma Sulaiman Hasan Mandilawi. Effect of daylight application on the thermal performa iraqi traditional vernacula residential buildings. Master's thesis, The University of Arizona, College of Architecture and Landscape Architecture, School of Architecture, 2012.

[83] J. Martens-Mullaly and G. Waters. Casey tree manual: Vision for the future: Casey–creating the most caring, safe, innovative and sustainable city, 2005.

[84] Gioia D. Massa and Simon Gilroy. Touch modulates gravity sensing to regulate the growth of primary roots of Arabidopsis thaliana. *Plant Journal*, 33(3):435–445, 2003. ISSN 09607412. doi: 10.1046/j.1365-313X.2003.01637.x.

[85] Mitra Mazarei, Irina Teplova, M. Reza Hajimorad, and C. Neal Stewart. Pathogen phytosensing: Plants to report plant pathogens. *Sensors*, 8(4):2628–2641, 2008. ISSN 1424-8220. doi: 10.3390/s8042628. URL http://dx.doi.org/10.3390/s8042628.

[86] Barbara Mazzolai, Cecilia Laschi, Paolo Dario, Sergio Mugnai, and Stefano Mancuso. The plant as a biomechatronic system. *Plant Signaling & Behavior*, 5(2):90–93, 2010. doi: 10.4161/psb.5.2.10457. URL http://dx.doi.org/10.4161/psb.5.2.10457.

[87] Barbara Mazzolai, Lucia Beccai, and Virgilio Mattoli. Plants as model in biomimetics and biorobotics: New perspectives. *Frontiers in Bioengineering and Biotechnology*, 2:2, 2014. ISSN 2296-4185. doi: 10.3389/fbioe.2014.00002. URL http://dx.doi.org/10.3389/fbioe.2014.00002.

[88] Mamoru Mekata. Kagome: The story of the basketweave lattice. *Physics Today*, 56(2):12, 2003.

[89] Christian Mercat. Les entrelacs des enluminures celtes. *Pour la science*, pages Faîtes–vos, 1997.

[90] Fernando Migliaccio, Paola Tassone, and Alessio Fortunati. Circumnutation as an autonomous root movement in plants. *American Journal of Botany*, 100(1):4–13, 2013. ISSN 00029122. doi: 10.3732/ajb.1200314.

[91] Minneapolis Riverfront Development Initiative. *RiverFIRST: a Park Design Proposal and Implementation Framework for the Minneapolis Upper Riverfront.* Minneapolis Park and Recreation Board, City of Minneapolis, and Minneapolis Parks Foundation, 2012. URL http://www.slideshare.net/MplsRiverfrontDesign/riverfirst-vision-april-2012.

[92] B Moulia, C Coutand, and J L Julien. Mechanosensitive control of plant growth: bearing the load, sensing, transducing, and responding. *Front Plant Sci*, 6(February):52, 2015. ISSN 1664-462X. doi: 10.3389/fpls.2015.00052. URL http://www.ncbi.nlm.nih.gov/pubmed/25755656.

[93] Bruno Moulia. Plant biomechanics and mechanobiology are convergent paths to flourishing interdisciplinary research. *Journal of Experimental Botany*, 64(15):4617–4633, 2013.

[94] Sergio Mugnai, Elisa Azzarello, Elisa Masi, Camilla Pandolfi, and Stefano Mancuso. Nutation in plants. In Stefano Mancuso and Sergey Shabala, editors, *Rhythms in Plants: Dynamic Responses in a Dynamic Environment*, chapter 2, pages 19–34. Springer International Publishing, Cham, 2015. ISBN 9783319205175. doi: 10.1007/978-3-319-20517-5_2. URL http://dx.doi.org/10.1007/978-3-319-20517-5{_}2.

[95] Gavin Munro and Full Grown. Human factor endless prototyping. Published as short term exhibition of work, 2016. Exhibition at Ars Electronica, held at the Drive Volkswagon Group Forum in Berlin, Germany.

[96] Danil Nagy, John Locke, and David Benjamin. Computational brick stacking for constructing free-form structures. In *Modelling Behaviour*, pages 203–212. Springer, 2015.

[97] Ali Nazari. Compressive strength of geopolymers produced by ordinary portland cement: Application of genetic programming for design. *Materials & Design*, 43:356–366, 2013.

[98] Sandra Oliveira, Henrique Andrade, and Teresa Vaz. The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in lisbon. *Building and Environment*, 46(11):2186 – 2194, 2011. ISSN 0360-1323. doi: 10.1016/j.buildenv.2011.04.034. URL http://dx.doi.org/10.1016/j.buildenv.2011.04.034.

[99] Theoharis Ouzounis, Eva Rosenqvist, and Carl-Otto Ottosen. Spectral Effects of Artificial Light on Plant Physiology and Secondary Metabolism: A Review. *HortScience*, 50 (8):1128–1135, aug 2015. URL http://hortsci.ashspublications.org/content/50/8/1128.abstract.

[100] Biranchi Narayan Panda, MVA Raju Bahubalendruni, and Bibhuti Bhusan Biswal. A general regression neural network approach for the evaluation of compressive strength of fdm prototypes. *Neural Computing and Applications*, 26(5):1129–1136, 2015.

[101] Anna Lisa Paul, Ray M. Wheeler, Howard G. Levine, and Robert J. Fer. Fundamental plant biology enabled by the space shuttle. *American Journal of Botany*, 100(1):226–234, 2013. ISSN 00029122. doi: 10.3732/ajb.1200338.

[102] Ronald Pierik and Mieke De Wit. Shade avoidance: Phytochrome signalling and other aboveground neighbour detection cues. *Journal of Experimental Botany*, 65(11):2815–2824, 2014. ISSN 14602431. doi: 10.1093/jxb/ert389.

[103] Corn M J Pieterse, Ronnie de Jonge, and Roeland L Berendsen. The soil-borne supremacy. *Trends in plant science*, 21(3):171173, March 2016. ISSN 1360-1385. doi: 10.1016/j.tplants.2016.01.018. URL https://doi.org/10.1016/j.tplants.2016.01.018.

[104] Daniel Piker. Kangaroo: form finding with computational physics. *Architectural Design*, 83(2):136–137, 2013.

[105] P Potluri, A Rawal, M Rivaldi, and I Porat. Geometrical modelling and control of a triaxial braiding machine for producing 3d preforms. *Composites Part A: Applied Science and Manufacturing*, 34(6):481–492, 2003.

[106] Mohammad H Rafiei, Waleed H Khushefati, Ramazan Demirboga, and Hojjat Adeli. Neural network, machine learning, and evolutionary approaches for concrete material characterization. *ACI Materials Journal*, 113(6), 2016.

[107] Ahmad Rafsanjani, Véronique Brulé, Tamara L Western, and Damiano Pasini. Hydro-responsive curling of the resurrection plant Selaginella lepidophylla. *Scientific reports*, 5 (8064):1–7, 2015. ISSN 2045-2322. doi: 10.1038/srep08064. URL http://www.nature.com/srep/2015/150127/srep08064/full/srep08064.html.

[108] Sohel Rana and Raul Fangueiro. *Braided structures and composites: production, properties, mechanics, and technical applications*, volume 3. CRC Press, 2015.

[109] Richard Reames. *Arborsculpture: Solutions for a small planet.* Arborsmith Studios, 2005.

[110] Richard Reames and Barbara Hahn Delbol. *How to grow a chair: the art of tree trunk topiary.* Arborsmith Studios, 1995.

[111] Donald Richardson. Maypole braider having a three under and three over braiding path, November 2 1993. US Patent 5,257,571.

[112] Mark Richardson, Alex Vittouris, and Geoff Rose. Socialised transport: Increasing travel mode diversity through open-source vehicle design, upcycling, natural production and distributed production methods. In *Australasian Transport Research Forum 2010 Proceedings*, 2010.

[113] Sarah Robinson, Agata Burian, Etienne Couturier, Benoit Landrein, Marion Louveaux, Enrique D. Neumann, Alexis Peaucelle, Alain Weber, and Naomi Nakayama. Mechanical control of morphogenesis at the shoot apex. *Journal of Experimental Botany*, 64(15):4729–4744, 2013. doi: 10.1093/jxb/ert199. URL https://dx.doi.org/10.1093/jxb/ert199.

[114] Jean-David Rochaix. Regulation and dynamics of the light-harvesting system. *Annual review of plant biology*, 65:287–309, 2014. ISSN 1545-2123. doi: 10.1146/annurev-arplant-050213-040226. URL http://www.scopus.com/inward/record.url?eid=2-s2.0-84899761322{&}partnerID=tZOtx3y1.

[115] Alexander V. Ruban. Evolution under the sun: Optimizing light harvesting in photosynthesis. *Journal of Experimental Botany*, 66(1):7–23, 2015. ISSN 14602431. doi: 10.1093/jxb/eru400.

[116] Justin B. Runyon, Mark C. Mescher, and Consuelo M. De Moraes. Volatile Chemical Cues Guide Host Location and Host Selection by Parasitic Plants. *Science*, 313(5795):1964–1967, 2006. ISSN 0036-8075. doi: 10.1126/science.1131371. URL http://www.sciencemag.org/cgi/doi/10.1126/science.1131371.

[117] Ulf G. Sandström. Green infrastructure planning in urban sweden. *Planning Practice and Research*, 17:373–385, 2002. doi: 10.1080/02697450216356. URL http://dx.doi.org/10.1080/02697450216356.

[118] Shaina Saporta, Frances Yang, and Matthew Clark. Design and delivery of structural material innovations. In *Structures Congress 2015*, pages 1253–1265, 2015.

[119] John Schaeffer, Stephanie Kotin, and Christopher Tebbutt. Willow dome. Early growth images published by the architects in [120], later growth image by author published in [15], republished in [29], 3, 1996. Built structure at the Real Goods Solar Living Center in Hopland, California, USA.

[120] John Schaeffer, David Arkin, Nancy Hensley, Adam Jackaway, Bruce King, Stephanie Kotin, Stephen Morris, Baile Oakes, Jeff Oldham, Christopher Tebbutt, Sim Van der Ryn, and Mark Winkler. *A Place in the Sun: The Evolution of the Real Goods Solar Living Center*. Chelsea Green Publishing Company, 1997.

[121] Vera Schmitz. Moebel aus dem Garten: Einzigartiges Naturdesign bei Full Grown aus England. *AIT*, 2016(3):142–143, 2016.

[122] A. R. Schrank. Plant tropisms. *Annual Review of Plant Physiology*, 1(1):59–74, 1950.

[123] Livia Camilla Trevisan Scorza and Marcelo Carnier Dornelas. Plants on the move: Towards common mechanisms governing mechanically-induced plant movements. *Plant signaling & behavior*, 6(12):1979–1986, 2011.

[124] Sanjeev Shankar. Living root bridges: State of knowledge, fundamental research and future application. In *IABSE Symposium Report*, volume 105, pages 1–8. International Association for Bridge and Structural Engineering, 2015.

[125] Tomasz Skrzypczak, Rafa Krela, Wojciech Kwiatkowski, Shraddha Wadurkar, Aleksandra Smoczyska, and Przemysaw Wojtaszek. Plant science view on biohybrid development. *Frontiers in Bioengineering and Biotechnology*, 5:46, 2017. ISSN 2296-4185. doi: 10.3389/fbioe.2017.00046. URL https://www.frontiersin.org/article/10.3389/fbioe.2017.00046.

[126] Ruth Slavid. *Wood architecture*. Laurence King Publishing, 2005.

[127] Virginia Stovin. The potential of green roofs to manage urban stormwater. *Water and Environment Journal*, 24(3):192–199, 2010.

[128] Tiziana Susca, Stuart R. Gaffin, and G. R. Dell'Osso. Positive effects of vegetation: Urban heat island and green roofs. *Environmental pollution*, 159(8):2119–2126, 2011.

[129] Yuichiro Takeuchi. Printable hydroponic gardens: Initial explorations and considerations. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems*, pages 449–458. ACM, 2016.

[130] Xiaodong Tang, John D. Whitcomb, Ajit D. Kelkar, and Jitendra Tate. Progressive failure analysis of 2×2 braided composites exhibiting multiscale heterogeneity. *Composites Science and Technology*, 66(14):2580–2590, 2006.

[131] Frank W. Telewski. Is windswept tree growth negative thigmotropism? *Plant Science*, 184:20–28, 2012. ISSN 01689452. doi: 10.1016/j.plantsci.2011.12.001. URL http://dx.doi.org/10.1016/j.plantsci.2011.12.001.

[132] Matthias Teschner, Bruno Heidelberger, Matthias Müller, Danat Pomerantes, and Markus H Gross. Optimized spatial hashing for collision detection of deformable objects. In *Vmv*, volume 3, pages 47–54, 2003.

[133] Wilfred Thesiger. *The marsh arabs*. Penguin, 2007.

[134] Masatsugu Toyota and Simon Gilroy. Gravitropism and mechanical signaling in plants. *American Journal of Botany*, 100(1):111–125, 2013. ISSN 00029122. doi: 10.3732/ajb.1200408.

[135] Anthony Trewavas. The foundations of plant intelligence. *Interface Focus*, 7(3):20160098, 2017. ISSN 2042-8898, 2042-8901. doi: 10.1098/rsfs.2016.0098. URL http://rsfs.royalsocietypublishing.org/content/7/3/20160098.

[136] Konstantinos Tzoulas, Kalevi Korpela, Stephen Venn, Vesa Yli-Pelkonen, Aleksandra Kaźmierczak, Jari Niemela, and Philip James. Promoting ecosystem and human health in urban areas using green infrastructure: A literature review. *Landscape and urban planning*, 81(3):167–178, 2007. URL http://dx.doi.org/10.1016/j.landurbplan.2007.02.001.

[137] Thomas Vallas and Luc Courard. Using nature in architecture: Building a living house with mycelium and trees. *Frontiers of Architectural Research*, 6(3):318 – 328, 2017. ISSN 2095-2635. doi: https://doi.org/10.1016/j.foar.2017.05.003. URL http://www.sciencedirect.com/science/article/pii/S2095263517300353.

[138] Filip Vandenbussche and Dominique Van Der Straeten. Shaping the shoot: A circuitry that integrates multiple signals. *Trends in Plant Science*, 9(10):499–506, 2004. ISSN 13601385. doi: 10.1016/j.tplants.2004.08.002.

[139] Visiondivision and Politecnico di Milano. The patient gardener. Images by author and published in [29], 35, 2011. Built structure in Milano, Italy.

[140] Mostafa Wahby, Daniel Nicolas Hofstadler, Mary Katherine Heinrich, Payam Zahadat, and Heiko Hamann. An evolutionary robotics approach to the control of plant growth and motion: Modeling plants and crossing the reality gap. In *Self-Adaptive and Self-Organizing Systems (SASO), 2016 IEEE 10th International Conference on*, pages 21–30. IEEE, 2016.

[141] Yihai Wang and Kevin M. Folta. Contributions of green light to plant growth and development. *American Journal of Botany*, 100(1):70–78, 2013. ISSN 00029122. doi: 10.3732/ajb.1200354.

[142] Jon Warnes. *Living willow sculpture*. Search Press, 2000.

[143] Stephanie Weber, Natasha Sadoff, Erica Zell, and Alex de Sherbinin. Policy-relevant indicators for mapping the vulnerability of urban populations to extreme heat events: A case study of philadelphia. *Applied Geography*, 63:231 – 243, 2015. ISSN 0143-6228. doi: 10.1016/j.apgeog.2015.07.006. URL http://dx.doi.org/10.1016/j.apgeog.2015.07.006.

[144] Irwin Weintraub. The role of grey literature in the sciences. *Access [Brooklyn College Library]*, 10, 2000.

[145] K. S. Werk and J. Ehleringer. Non-random leaf orientation in Lactuca serriola L. *Plant, Cell & Environment*, 7(2):81–87, 1984. ISSN 1365-3040. doi: 10.1111/j.1365-3040.1984.tb01560.x. URL http://onlinelibrary.wiley.com/doi/10.1111/j.1365-3040.1984.tb01560.x/.

[146] Arthur Wiechula. Schneeschutzzaun aus verflochtenen Pflanzen (A snow fence of interlaced plant), December 21 1923. URL https://www.google.com/patents/DE386940C?cl=en. DE Patent 386,940.

[147] Arthur Wiechula. Verfahren zum Vereinigen von Baumteilen (A method for combining parts of trees), May 18 1928. URL https://www.google.com/patents/DE459996C?cl=en. DE Patent 459,996.

[148] Raphael Winick. Copyright protection for architecture after the architectural works copyright protection act of 1990. *Duke Law Journal*, 41(6):1598–1651, 1992.

[149] Lei Xu, Seong Jong Kim, Cheng-Huat Ong, and Sung Kyu Ha. Prediction of material properties of biaxial and triaxial braided textile composites. *Journal of Composite Materials*, 46(18):2255–2270, 2012.

[150] Payam Zahadat and Thomas Schmickl. Generation of diversity in a reaction-diffusion-based controller. *Artificial life*, 20(3):319–342, 2014.

[151] Payam Zahadat, Daniel Nicolas Hofstadler, and Thomas Schmickl. Vascular morphogenesis controller: A generative model for developing morphology of artificial structures. In *Proceedings of the Genetic and Evolutionary Computation Conference*, GECCO '17, pages 163–170, New York, NY, USA, 2017. ACM. ISBN 978-1-4503-4920-8. doi: 10.1145/3071178.3071247. URL http://doi.acm.org/10.1145/3071178.3071247.